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14. ABSTRACT

NAVAIRSYSCOM has evaluated the individual benefits of 3 different thermal stability improving additives (TSIAs) in jet fuel using 2 separate, small-scale test devices - one laminar flow and the other turbulent. Both systems pump fuel at constant flowrate and use stainless steel tubes that are heated to maintain the bulk fuel at a constant, elevated test temperature. The laminar device has an inside diameter of 0.1 in. (0.262 cm) and an approximate Reynolds No. of 200, whereas the turbulent has an inside diameter of 0.01 in. (0.0254 cm) and a Reynolds No. of 13,000. The results have shown that all 3 TSIAs, when test at their maximum dose levels, reduce the amount of thermal deposits (measured via carbon burnoff) in both flow regimes for 3 different base fuels tested. Both units rank the level of thermal stability in the same order for the 3 baseline fuels tested. In addition, both devices show that Betz 8Q462 is the most effective additive of the 3 tested, with MDA demonstrating almost similar performance in controlling deposit formation. Furthermore, Betz 8Q406 was not as effective as the 2 other additives, but a change in its formulation by the addition of 2 mg/l MDA (to produce 8Q462) greatly improved its performance in both test devices, but most notably in the laminar unit. However, one exception had occurred when MDA was added to one of the test fuels (Tank 20/22), which caused an increase in deposition compared to the neat fuel when tested in the turbulent unit. Overall, the combination of the accelerated test conditions in the turbulent unit of higher bulk fuel temperate, higher flowrate, turbulent flow (i.e., flatter temperature profile across the tub ID), and shorter residence time make this a more severe test when compared to the laminar device.

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EVALUATION OF THERMAL STABILITY IMPROVING ADDITIVES FOR JET FUEL IN BOTH LAMINAR AND TURBULENT FLOW TEST UNITS

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ABSTRACT

The Naval Air Systems Command has evaluated the individual benefits of three (3) different thermal stability improving additives (TSIAs) in jet fuel using two (2) separate, small-scale test devices - one laminar flow and the other turbulent. Both systems pump fuel at constant flowrate and use stainless steel tubes that are heated to maintain the bulk fuel at a constant, elevated test temperature. The laminar device has an inside diameter of 0.1 inches (0.262 cm) and an approximate Reynolds Number of 200, whereas the turbulent has an inside diameter of 0.01 inches (0.0254 cm) and a Reynolds Number of 13,000. The results have shown that all three (3) TSIAs, when tested at their maximum dose levels, reduce the amount of thermal deposits (measured via carbon burnoff) in both flow regimes for three (3) different base fuels tested. Both units rank the level of thermal stability in the same order for the 3 baseline fuels tested. In addition, both devices show that Betz 8Q462 is the most effective additive of the three tested, with MDA demonstrating almost similar performance in controlling deposit formation. Furthermore, Betz 8Q406 was not as effective as the two other additives, but a change in its formulation by the addition of 2 mg/l MDA (to produce 8Q462) greatly improved its performance in both test devices, but most notably in the laminar unit. However, one exception had occurred when MDA was added to one of the test fuels (Tank 20/22), which caused an increase in deposition compared to the neat fuel when tested in the turbulent unit. Overall, the combination of the accelerated test conditions in the turbulent unit of higher bulk fuel temperature, higher flowrate, turbulent flow (i.e., flatter temperature profile across the tube ID), and shorter residence time make this a more severe test when compared to the laminar device.

NOMENCLATURE

ASTM – American Society for Testing and Materials

BPT – Breakpoint Temperature, as measured in the JFTOT

CBO – Carbon Burnoff, as measured in the LECO Carbon Analyzer

HiReTS – High Reynold's Number Thermal Stability test unit

JFTOT – Jet Fuel Thermal Oxidation Tester

JPTS – Jet Fuel Thermally Stable

ppb – part per billion

ppm – part per million

Re – Reynold's Number

Shell TRC – Shell Thornton Research Centre

STR – Single Tube Reactor

TSIA – Thermal Stability Improving Additive

1. INTRODUCTION

The thermal oxidative stability of jet fuel (viz., JP-5), i.e., the characteristic of the fuel to absorb heat without forming solid deposits, is an essential factor in the design of high performance aircraft. Vital components of the aircraft require cooling during flight, and the fuel is an essential part of the thermal management scheme. Since the fuel is the primary heat transfer media available, it is recirculated through various heat exchangers in the aircraft fuel system, thus causing fuel temperatures to reach 150°C (302°F) or higher[1]. At such elevated temperatures, many studies have shown that the fuel is at its thermal limit, i.e., any further rise in the fuel temperature will cause unacceptable amounts of deposits to form in critical components of the aircraft fuel system.

For this reason, improvement of bench-scale, laboratory test units that study jet fuel thermal stability are vital to more accurately assess the impact of these deposits in actual aircraft. Currently, the Jet Fuel Thermal Oxidation Tester (JFTOT), a quality control test, is used to assess the fuel thermal stability by means of the Breakpoint Temperature (BPT). This value is only qualitative and is not useful in terms of estimating the quantity of deposits that form in an aircraft engine fuel system at these elevated fuel temperatures. This shortcoming in the JFTOT led to the development of the U.S. Navy's test unit, the Single Tube Reactor (STR), which thermally stresses fuel at, or slightly above the fuel temperatures experienced in an actual aircraft. In order to better quantify a fuel's deposition tendency, this unit was designed with various consumable, deposit-collecting components which are subjected, post test, to a carbon burnoff (CBO) analysis which provides quantitative carbon deposition data (in μg).

The fuel flow through the STR, however, is laminar ($Re < 2000$), and test units that operate in this flow regime have been considered to give erroneous results when thermal stability improving additives (TSIAs) are tested. This objection dates back to the theory that the JFTOT, because it is operated in the laminar flow regime, is "fooled" by additives[2]. In other words, since the JFTOT is operated under less severe test conditions as compared to turbulent units, the JFTOT results may indicate the fuel's thermal stability is better than it would be if tested in a turbulent flow device or used in an actual aircraft. On the other hand, all of the turbulent flow devices up to this time have been considered non-ideal laboratory tools because they consume too much fuel for a single determination, are time consuming, and are relatively complex to operate and maintain[3].

In considering these problems, Shell Thornton Research Centre (TRC) undertook the task of developing a small-scale device to evaluate fuel thermal stability under more realistic conditions. A pre-production prototype device, termed the High Reynolds Number Thermal Stability (HiReTS) test unit, has been developed as a quality control test for jet fuel and as a potential replacement for the JFTOT[4]. Recently, the U.S. Navy at NAS Patuxent River, MD was provided with the opportunity to evaluate this unit on a suite of fuels. The results of this study have been presented earlier and have indicated the usefulness of such a test[5]. In further exploration of the HiReTS, the U.S. Navy has also evaluated the effects of proven TSIAs to inhibit fuel thermal deposition in a turbulent flow regime.

The overall objective of this research paper is to make a direct comparison of the effects of TSIAs in a laminar device (the STR) with the turbulent flow HiReTS. The results should provide insight into the influence of fuel velocity (viz., residence time and Re) on deposition for fuels doped with and without various TSIAs.

2. EXPERIMENTAL

2.1 **Test Units.** Table 1 shows detailed specifications for the two units. As shown, the Reynolds Numbers (Re) are calculated to be 200 and 13,000 for the laminar and turbulent units, respectively.

The ***laminar*** unit has a flowrate of 10 mL/min and test duration of twelve (12) hours. The heater tube consists of a contiguous 8-inch length of 1/8" OD stainless steel tubing (4 inches each for the Pre- & Main Heaters) with appropriate compression fittings on each end. It is heated by two (2) sets of identical heating systems - one (1) for the Pre-Heater section and 1 for the Main Heater section, as shown in Figure 1. Each heating system uses copper blocks that consist of 2 identical halves that are snugly fitted around the contiguous heater tube. Each half contains 2 bores in which heater cartridges are snugly inserted and secured, for a total for four (4) cartridges per heater section. All 4 cartridges (for each heater section) are electrically heated using 1 variable power supply. These heaters are operated to control the bulk fuel temperatures exiting the Pre-Heater and Main Heater sections to values of 121°C (250°F) and 191°C (375°F), respectively. To accomplish this task, the Pre-Heater block temperature is controlled to 258°C (496°F), and the Main Heater block temperature is allowed to fluctuate in order to maintain the bulk fuel temperature immediately exiting this block to be 191°C (375°F). As a result, the outside wall temperature for the Main Heater section can range anywhere from 325-400°C (617-752°F).

The relatively long fuel residence time (0.82 seconds per inch or 4.1 seconds of total effective heated length) in the STR is sufficient to generate measurable (carbon) deposits in the system's test sections. These components, i.e., the Pre-Heater & Main Heater tubes, downstream fittings, and 0.5 μm filter are subsequently analyzed for carbon content via CBO analysis using a LECO carbon analyzer. For this particular study only the deposits collected and measured in the Pre-Heater & Main Heater tubes are used for comparison with those of the turbulent unit, which only collects tube deposits.

The ***turbulent*** device (HiReTS) uses a fuel flowrate of 35 mL/min and is heated electrically via bus bars clamps to maintain the bulk fuel temperature immediately exiting the capillary tube to 290°C (554°F), as shown in Figure 2. Under these conditions, the fuel residence time is 0.01 sec and the maximum outside wall temperature can vary from 380-400°C (716-752°F); this is measured via a motor driven pyrometer that scans the capillary surface at nine (9) different positions, 2.5 mm apart, over the last 21-mm of the effective heated length. The test duration for a standard, quality control (QC) test as established by Shell TRC is 2 hours, but was allowed to vary for these experiments so that sufficient (carbon) deposits could be produced to achieve a capillary failure condition (see Note 1 of Table 1 for definition of failure). Therefore, without the aid of a pre-heater, the HiReTS requires a relatively large amount of heat to raise the fuel temperature across the capillary from ambient to the (controlled) fuel exit temperature. As a result, deposits form inside the tube at the fuel/metal interface which have an insulating effect that 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 2 simultaneous phenomena, the capillary surface temperature increases, viz. 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 9 scan positions (from the lowest value obtained at the beginning of the test to the end-of-test value) is called the HiReTS Number. In addition, the effective heated length of the capillary (5.3125") is cut into four (4) equal sections (approximately 1.3" each) for a subsequent CBO analysis. In this study, the test duration was varied until a capillary failure condition was achieved (HiReTS Number = 1000), and the test duration required to reach this condition can be viewed as the useful "life" of the capillary (in hours) for any given base (unadditized) fuel run under these test conditions. Furthermore, the effectiveness of any TSIA could be measured as the reduction in deposition that the additive provides in any given base fuel, or alternatively, as the extension of "life" the TSIA provides over the unadditized fuel. However, the latter measurement does always accurately reflect the amount of carbon deposits present inside the capillary during a given test since only a tenuous correlation exists between the HiReTS Number and the weight of carbon deposits formed in the capillary tube.

2.2 **Fuels.** The three (3) fuels selected for this study are considered marginal with respect to their stability as defined by the JFTOT BPT. A brief description of these fuels follows.

2.2.1 ***Red Hill Tank 4*** – A JP-5 fuel containing 60 ppm of nitrogen that was refined on the U.S. West Coast in the early 1990s. The fuel passed the JFTOT specification at the refinery, but changed to off-specification in storage. The JFTOT BPT was measured to be 245°C in 1993; a recent JFTOT test in March 2000 showed the fuel stability had improved to a BPT of 255°C. The copper content was measured to be 7 ppb.

2.2.2 ***Tank 20/22*** – A JP-5 that contains 50 ppb of copper, which is on the low end of copper contamination normally experienced in the fleet. This fuel has a BPT of 265°C.

2.2.3 ***Tank 17/19*** – A typical JP-5 with a JFTOT BPT of 270°C. The copper content was measured to be 17 ppb.

2.3 Thermal Stability Improving Additives (TSIAs):

2.3.1 ***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 for fuels additized with MDA.

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

2.3.3 ***Betz 8Q462*** - This additive comprises Betz 8Q406 plus 2 mg/L MDA, and is diluted with a 50:50 mixture of naptha solvent. It is used at a concentration of 256 ppm (v/v) in practice as well as throughout this test program, and has the same amount of active ingredient as the Betz 8Q406.

3. RESULTS AND DISCUSSION

3.1 **Baseline Tests.** The initial step of this study was to determine the thermal stability of the three baseline fuels in both units, i.e., before the addition of TSIAs. A comparison was then made to evaluate the effectiveness of each additive in reducing surface deposits, and how this level of reduction was influenced by the differences in fuel velocity (i.e., residence time and Re) between the 2 test devices.

Upon completion of the baseline tests, a CBO analysis was made on the heated tube sections in order to quantify the deposits. These data are shown in Table 2 and are expressed as µg/hr, where the value for total heated-tube surface deposits (in µg) is divided by the test duration (in hours). Then, a comparison was made on how each device ranks the level of stability, where the number "[1]" indicates the highest level. Despite the difference in operating conditions, both units ranked the level of stability the same, with Red Hill Tank 4 demonstrating the highest level and Tank 17/19 showing the lowest. However, as shown in Table 2, this agreement is contrary to that of JFTOT BPT, which shows a complete reversal in ranking results. It should be noted here that the JFTOT uses a qualitative measurement that is based on a subjective comparison of the color of the tube deposits (post test) to that of the Color Standard established by American Society of Testing and Materials (ASTM).

3.2 **The Study of TSIAs Under Laminar Conditions.** A reduction in surface deposition rate (µg/hr) caused by the addition of each additive to each baseline fuel, as tested in the STR, is shown in Table 3. As another means of evaluating the effect of each TSIA, the rate data is also included for a thermally stable jet fuel, JPTS, which has been evaluated under identical operating conditions. As shown in the table, a significant improvement (reduction) in deposition rates is observed with the additized fuels in comparison to that of the neat fuels.

A comparison of the averages for surface deposition rates and percent reduction in surface deposits among the 3 TSIAs in the 3 test fuels show that Betz 8Q462 is the most effective, with MDA coming in a close second, then followed by the Betz 8Q406. This level of effectiveness was expected before this study even commenced. In addition, the STR was able to detect the beneficial effects of adding 2 mg/l MDA to Betz 8Q406 (to thus produce Betz 8Q462) in all 3 fuels, and is a very significant improvement in the formulation[6].

3.3 **The Study of TSIAs Under Turbulent Conditions.** The influence of the TSIAs on the deposition rate of the same matrix of fuels under turbulent flow conditions is shown in Table 4. This data is a measure of the time it takes for the turbulent unit to reach a HiReTS Number of 1000. Earlier studies made by Shell during the developmental stage of this unit estimated this number equates approximately to a Code 3 deposit in the JFTOT. Therefore, in the study of TSIAs, it is assumed that when a HiReTS Number of 1000 is reached, the capillary tube has collected a significant amount of deposits, and it is at this point that the deposition rate is rapidly approaching or has entered the post-induction period. At this time, the collection efficiency of the capillary, caused by deposit accumulation on the inside surface of the metal tube, is assumed to be exponentially approaching a plugging condition, and the test is then terminated.

During the planning stage of this study, the time to reach a HiReTS Number of 1000 was thought to be an indirect measure of the amount of deposit formed. Analysis of the data in Table 4 and 5, however, showed that only a weak correlation exists between HiReTS Number and carbon deposit weight. This was attributed mainly to the fact that deposition was occurring upstream of the 21-mm scan length and thus could not be detected by the pyrometer. Therefore, the HiReTS Number is better used to estimate the amount of deposits accumulated in the capillary tube and to determine when a test should be terminated, rather than an absolute measure of carbon deposition inside the tube. Without these pyrometer readings, it would be extremely difficult to determine when a test should be terminated when testing a fuel of higher (or lower) stability.

The correlation between HiReTS Number and deposition rate might be improved if a value lower than 1000 was used as the arbitrary failure condition. Figure 3 shows the tracking of the HiReTS Number versus test time for the baseline fuel Red Hill Tank 4, unadditized and with each TSIA added individually. It is quite apparent that the curves exhibit erratic behavior beyond a HiReTS Number of 600. These changes in surface outer wall temperature are most likely occurring as a result of the higher accumulation of surface deposits that inevitably affect the heat transfer from the tube wetted-wall to the bulk fuel stream. Therefore, using a lower HiReTS Number to represent the capillary failure time, where the condition of the surface is less complicated by the accumulation of excess amounts of deposits, may be a solution to the problem of poor correlation with CBO. Also, an added benefit is that the test duration could be shortened, which would also decrease the amount of fuel consumed for a given test.

Table 4 shows that all of the TSIAs were effective in reducing the surface deposit, with the exception of MDA in fuel Red Hill Tank 4. No explanation for this behavior has been offered at this time. A potential cause of this phenomenon may be the decomposition of MDA at this higher operating temperature, but further experiments will need to be conducted to verify this theory since no indication of this decomposition was evident in the other two fuels.

Trends of the beneficial behavior of the TSIAs in the turbulent unit are somewhat similar to those observed in the laminar unit. Since the reduction of the surface deposits by MDA is based on only 2 fuels, its performance behavior cannot be directly compared to Betz 8Q462 at this time. It can be generalized based on this small amount of data, however, that both additives performed equally well. In addition, both of these additives showed better effectiveness when compared to Betz 8Q406, which has also been demonstrated in the laminar device.

3.4 **The Effect of Laminar and Turbulent Flow on Additive Performance.** The differences in design and operation of the two units affect how test fuels are thermally stressed, viz., with the turbulent device having a flowrate that is three (3) times higher than the laminar device. To cause a sufficient amount of deposit to form in a reasonable time period, this unit must be run at a higher temperature than the laminar unit. The combination of accelerated conditions of higher bulk fuel temperature, higher flowrate, turbulent flow (i.e., flatter temperature profile across the tube ID), and shorter residence time should make this unit more severe than the laminar unit since a greater mass of fuel will be heated and undergo more thermal oxidative reactions at this elevated test temperature for a given test duration; thus, the deposition rate (in µg/hr) should be higher in the turbulent unit. However, the deposition rates for the neat fuels shown in Table 2 show quite the opposite. For example, Red Hill Tank 4 Neat has a rate of 109.9 µg/hr at 191°C (375°F) in the laminar unit, where as the rate observed at the more severe conditions of 290°C (554°F) in the turbulent unit is 33.9 µg/hr. The reason for this disparity is due to the unit of time used to calculate the rate term, which is based upon the total deposit weight (in µg) divided by the test duration (in hours). In addition, the total amount of deposit formed from the different quantities of fuel that passes through each unit's heated tube(s) has not been specified. To obtain a better measurement of deposition rates, each unit's deposit weight data must be normalized by the volume of fuel consumed during a given test, which yields deposit concentration (in µg/L), as shown in Table 6a. Then, this concentration needs to be divided by the fuel's residence time (in seconds) in the heated section to ultimately obtain this new, alternative rate expressed in µg/L-sec (see Table 6b).

In Table 6a, the concentration of deposits for Red Hill Tank 4 in the laminar and turbulent units, for example, is 183.2 and 16.1 µg/L, respectively; their respective deposition rates, as shown in Table 6b, are 44.7 and 1614.3 µg/L-sec. Based upon these alternative rates, the turbulent unit's operating conditions are considered more severe, and produce a deposition rate that is approximately 35 times greater than the laminar unit.

The data in Table 7 show the effect of these different operating conditions by making a comparison of the % reduction in surface deposits caused by the TSIAs. The % reduction is higher for the laminar unit, which states that the lower rate of deposition is controlled more efficiently in this regime of lower flow and temperature. The fact that the JFTOT shows MDA to be very effective at the end of its 2.5 hours test duration (by measurement of BPT) is due to the relatively low rate of deposit formation. Consequently, TSIAs will appear very effective if the unit's test conditions are less severe. To offset the low rate of deposition experienced in the JFTOT, MDA should be tested under extended duration to show the effect that this additive has on controlling tube surface deposition until some arbitrarily chosen failure condition is achieved.

4. CONCLUSIONS

a. Both units, the STR and HiReTS, rank the level of thermal stability in the same order for the 3 baseline fuels tested, with Red Hill Tank 4 having the highest level and Tank 17/19 having the lowest. However, this level of stability does not agree with the order based upon the JFTOT BPT, which shows a complete reversal in this order.

b. Both test units show that Betz 8Q462 is the most effective additive of the 3 tested. However, MDA showed almost similar performance to the Betz 8Q462 in controlling deposit formation.

c. Betz 8Q406 was not as effective as the two other additives, but a change in its formulation by the addition of 2 mg/l MDA (to produce 8Q462) greatly improved its performance in both test devices, but most notably in the laminar unit.

d. In test fuel Tank 20/22, MDA had caused an increase in deposition compared to the neat fuel when tested in the turbulent unit. No explanation for this behavior has been offered at this time. A potential cause of this phenomenon may be the decomposition of MDA at this higher operating temperature, but further experiments will need to be conducted to verify this theory since no indication of this decomposition was evident in the other two fuels.

e. Due to the poor correlation in the turbulent unit between HiReTS Number and CBO, the use of the HiReTS Number as an indirect measure of capillary tube deposition was not very accurate. However, the use of the HiReTS Number as an estimate of (carbon) deposition inside the capillary is useful in determining when a test should be terminated.

f. The combination of the accelerated test conditions in the turbulent unit of higher bulk fuel temperature, higher flowrate, turbulent flow (i.e., flatter temperature profile across the tube ID), and shorter residence time make this a more severe test when compared to the laminar device. This is due to the fact that a greater mass of fuel will be heated and undergo more thermal oxidative reactions at this elevated test temperature during a given test duration. The impact of this more severe operating condition is evident when using an alternative (carbon) deposition rate expressed in μg/L-sec.

5. RECOMMENDATIONS

a. Thermal stability studies should continue with both units in order to address the impact of recycling/recirculation on the depletion of TSIAs. Adjustments should be made in the temperatures of heated tube surfaces and bulk fuel to those experienced in actual aircraft. Furthermore, duplicate or triplicate tests should be conducted in each device to estimate the precision of the units.

b. The turbulent unit (HiReTS) should be modified for further research studies by incorporating a fuel pre-heater upstream of the main heater section and sintered steel filter(s) downstream of this main heater. This would enable the HiReTS to thermally stress fuels more closely to actual aircraft conditions and would allow deposits exiting the capillary to be collected and measured.

c. The 21-mm scan length of the HiReTS capillary should be increased to include a greater length of the heated tube, and would be ideal if the entire length could be scanned. This would provide additional heat transfer data and thus a possible improvement in the correlation of the HiReTS Number with the tube deposition rate. Another possible improvement to this correlation would be to change the capillary failure criteria by terminating the test when a HiReTS Number

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TABLE 1: TEST UNIT SPECIFICATIONS

	SS Tube Dimensions									Filter Porosities	
Test Unit	ID	Effective Heated Length	Fuel Residence Time	Flowrate	Pre-Heater Exit Temp	Main Heater Exit Temp	Re	System Pressure	Test Duration	Fuel Pre-Filter	Tube Exit Filter
	(inches)	(inches)	(sec)	(mL/min)	(°C)	(°C)	(unitless)	(psig)	(hours)	(µm)	(µm)
Laminar (STR)	0.1 (0.262 cm)	5 (12.7 cm)	4.1	10	121 (250°F)	191 (375°F)	200	500	12	2	0.5
Turbulent (HiReTS)	0.01 (0.0254 cm)	5.3125 (13.5 cm)	0.01	35	N/A(3)	290 (554°F)	13,000	500	Variable(1)(2)	20	N/A

NOTES:

(1) Run HiReTS until a HiReTS No. $\geq$ 1000 is achieved. For this study, 1000 is assumed to signify a capillary failure condition.
(2) Test duration for standard operating conditions (i.e., as a QC test) is 2 hours.
(3) N/A - "Not Aplicable." This signifies that this piece of equipment does not exist.

TABLE 2: THERMAL STABILITY MEASUREMENT OF NEAT FUELS

(Laminar vs. Turbulent Test Units)

		Heated Tube Deposition Rates	
Fuel Designation	**JFTOT BPT (^oC)**	**Laminar Unit (µg /hr)**	**Turbulent Unit (µg /hr)**
Red Hill Tank 4	255 [3]$^{(1)}$	109.9 [1]	33.9 [1]
Tank 20/22	265 [2]	168.5 [2]	62.1 [2]
Tank 17/19	270 [1]	176.5 [3]	70.0 [3]

NOTES:

(1) Numbers in brackets ([ ]) rank the order of stability, where number [1] is considered the most stable.

TABLE 3: THERMAL STABILITY MEASUREMENT OF ADDITIZED FUELS

(Laminar Unit)

	Surface Deposition Rates - Pre + Main Heaters (μg/hr)				% Reduction of Surface Deposits		
Fuel Designation	**Neat**	**MDA**	**8Q406**	**8Q462**	**MDA**	**8Q406**	**8Q462**
Red Hill Tank 4	109.9	32.3	67.9	22.5	70.6	38.2	79.5
Tank 20/22	168.5	31.6	46.7	29.6	81.2	72.3	82.4
Tank 17/19	176.5	39.6	135.1	25.2	77.8	23.5	85.7
Average	151.6	34.4	83.2	25.7	76.5	44.6	82.5
JPTS(1)	1.4						

NOTES:

(1) Included for reference and comparison, and tested under identical operating conditions as all other fuels/additives shown.

TABLE 4: THERMAL STABILITY MEASUREMENT OF ADDITIZED FUELS

(Turbulent Unit)

	Time to Capillary Failure (hours)(1)			
Fuel Designation	**Neat**	**MDA**	**8Q406**	**8Q462**
Red Hill Tank 4	8	7.2	12.3	21
Tank 20/22	0.45	1.05	0.7	7.2
Tank 17/19	1.9	25.5	8.7	19

NOTES:

(1) Capillary failure reached when HiReTS No. = 1000.

TABLE 5: THERMAL STABILITY MEASUREMENT OF ADDITIZED FUELS

(Turbulent Unit)

	Capillary Deposition Rate at Failure[1] (µg/hr)				% Reduction of Surface Deposits		
Fuel Designation	**Neat**	**MDA**	**8Q406**	**8Q462**	**MDA**	**8Q406**	**8Q462**
Red Hill Tank 4	33.9	20.5	31.5	8.8	39.5	7	74
Tank 20/22	62.1	118.5[2]	37.5	43	-90.8[2]	39.6	30.7
Tank 17/19	70	7.9	19.9	14.4	88.8	71.6	79.4
Average	55.3	14.2	33.5	22.1	64.2	39.4	61.4

NOTES:

(1) Capillary failure reached when HiReTS No. = 1000.

(2) These value 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.

TABLE 6a: EFFECT OF FLOW ON ADDITIVE PERFORMANCE

(Tube Deposition Concentration - Laminar vs. Turbulent)

	Tube Deposition Concentration at Failure[1] (µg/L)							
Fuel Designation	**Neat**		**MDA**		**8Q406**		**8Q462**	
	Laminar	*Turbulent*	*Laminar*	*Turbulent*	*Laminar*	*Turbulent*	*Laminar*	*Turbulent*
Red Hill Tank 4	183.2	16.1	53.8	9.8	113.2	15.0	37.5	4.2
Tank 20/22	280.8	29.6	52.7	56.4	77.8	17.9	49.3	20.5
Tank 17/19	294.2	33.3	66.0	3.8	225.2	9.5	42.0	6.9

TABLE 6b: EFFECT OF FLOW ON ADDITIVE PERFORMANCE

(Alternative Tube Deposition Rate - Laminar vs. Turbulent)

	Alternative Tube Deposition Rate at Failure[2] (µg/L-sec)							
Fuel Designation	**Neat**		**MDA**		**8Q406**		**8Q462**	
	Laminar	*Turbulent*	*Laminar*	*Turbulent*	*Laminar*	*Turbulent*	*Laminar*	*Turbulent*
Red Hill Tank 4	44.7	1614.3	13.1	976.2	27.6	1500.0	9.1	419.0
Tank 20/22	68.5	2957.1	12.8	5642.9	19.0	1785.7	12.0	2047.6
Tank 17/19	71.7	3333.3	16.1	376.2	54.9	947.6	10.2	685.7

NOTES:

(1) These values are calculated by taking total surface deposits (in µg) and dividing this value by the total fuel consumed during a given test (in liters).

(2) These rates are determined by taking tube deposition concentration (µg/L) and dividing it by the residence time (seconds), which yields deposition rate in µg/L-sec.

TABLE 7: EFFECT OF FLOW ON ADDITIVE PERFORMANCE

(% Reduction in Tube Surface Deposition - Laminar vs. Turbulent)

Fuel Designation	**MDA**		**8Q406**		**8Q462**	
	Laminar	*Turbulent*	*Laminar*	*Turbulent*	*Laminar*	*Turbulent*
Red Hill Tank 4	70.6	39.5	38.2	7	79.5	74
Tank 20/22	81.2	-90.8(1)(2)	72.3	39.6	82.4	30.7
Tank 17/19	77.8	88.8	23.5	71.6	85.7	79.4
Average	76.5	64.2	44.6	39.4	82.5	61.4

NOTES:

(1) These value are not included in the averages.
(2) This negative value actually indicates a % increase in deposition.

Figure 1: Schematic of Single Tube Reactor (STR)

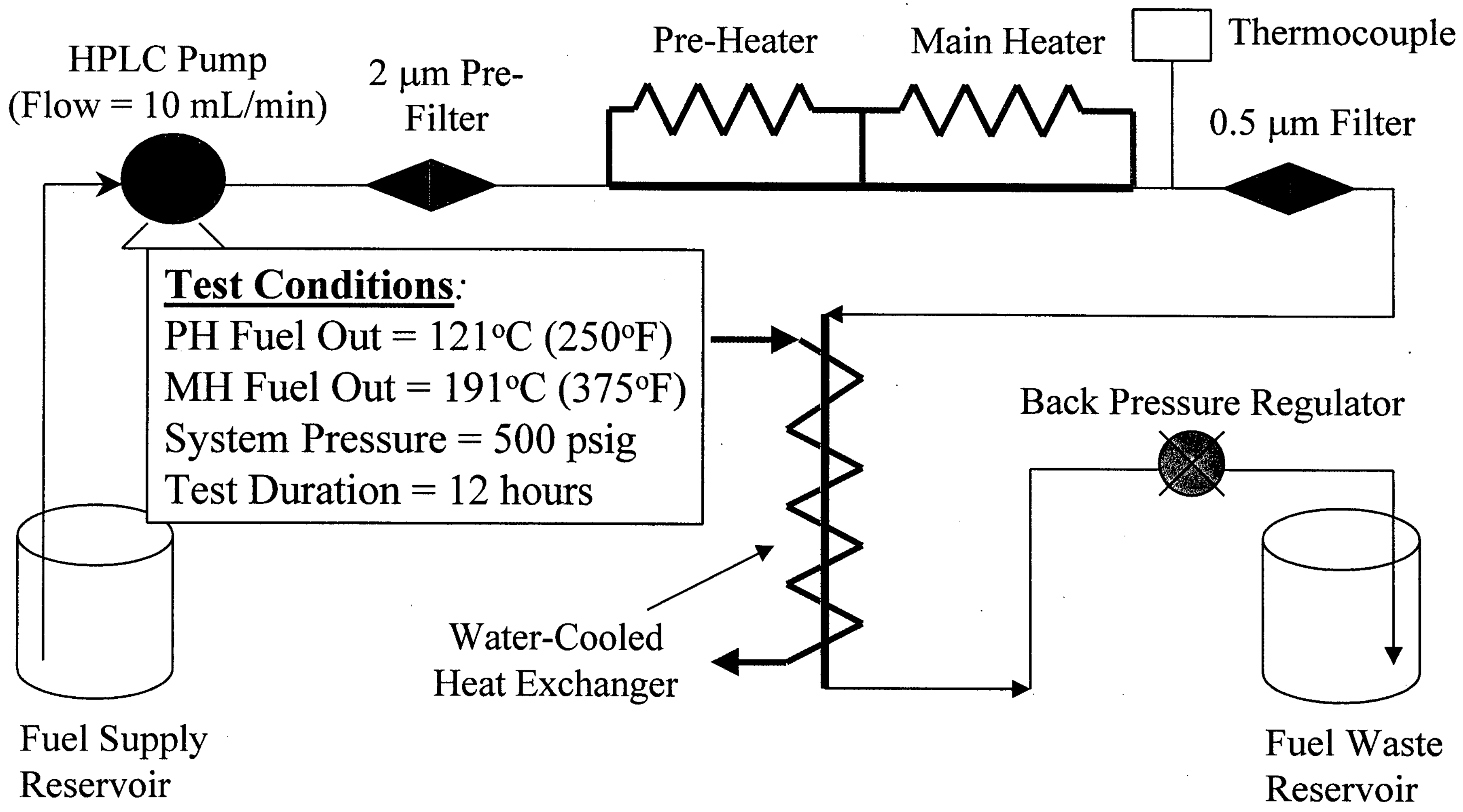

Figure 2: Schematic of HiReTS Test Unit

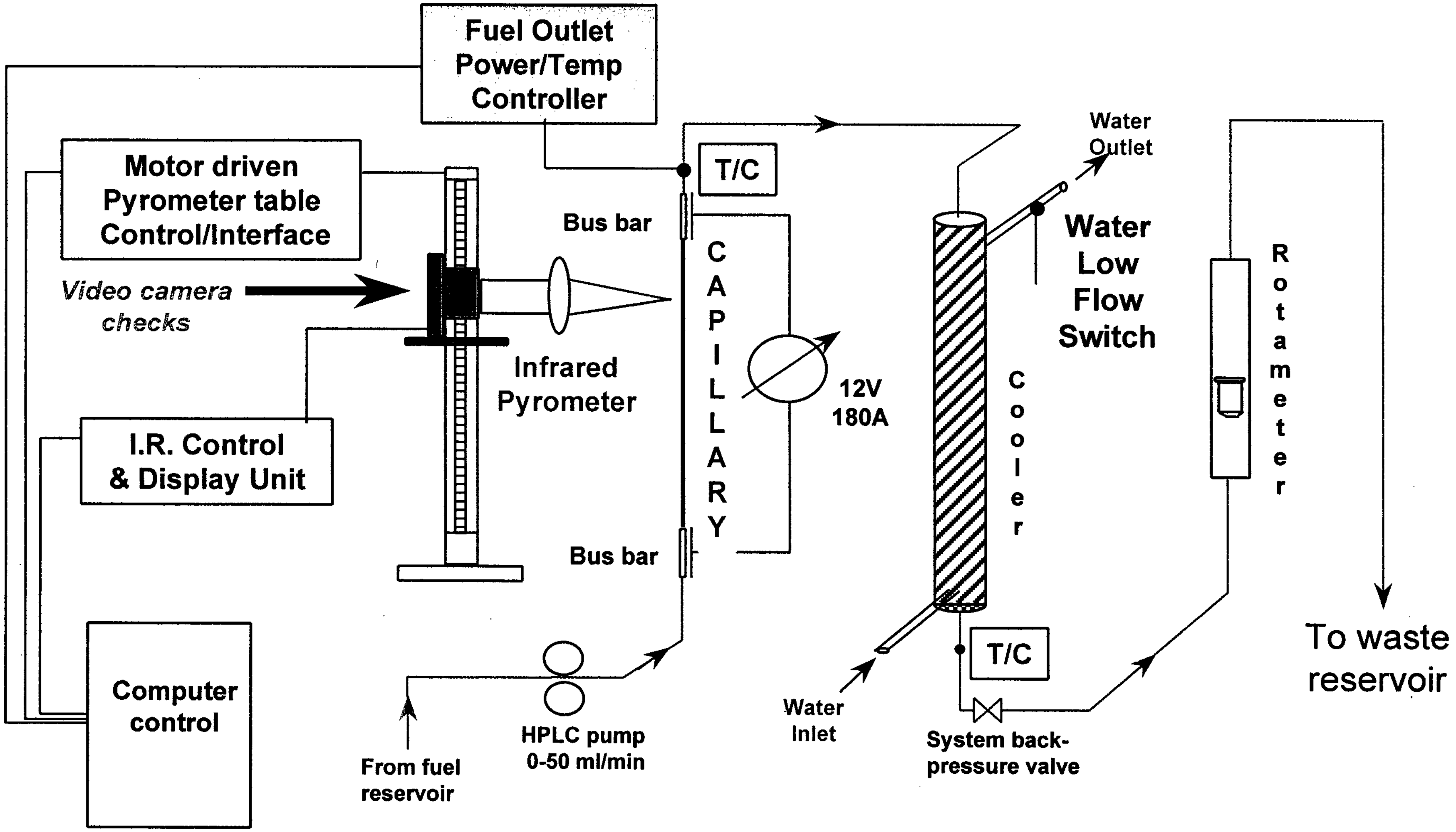

FIGURE 3: HiReTS DATA FOR RED HILL TANK 4

BPT = 255°C; Contains 60 ppm Nitrogen

Failure Time = Time to Reach HiReTS No. of 1000

(Failure Times Shown in Legend)