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IMPACT OF FUEL RECIRCULATION ON THERMAL STABILITY

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ABSTRACT

Modern military aircraft utilize aviation fuel for combustion energy and also as a heat sink to cool component systems. On-board fuel management must satisfy both combustion and cooling requirements during all phases of a flight. Frequently, fuel that has been subjected to thermal oxidative stress must be diverted from combustion and recirculated back to the fuel tanks. The resultant pre-stressing can significantly reduce fuel thermal stability. Through an isothermal simulation under well-defined reaction conditions, the thermal stability of neat and pre-stressed or recirculated fuels has been measured. It was found that fuel recirculation seriously degrades thermal stability. The results of this study are reported, and possible corrective measures are discussed.

INTRODUCTION

In addition to providing combustion energy, fuel in modern aircraft is utilized as a heat sink to cool component systems.[1] Exposure to heated surfaces and the presence of dissolved oxygen can lead to the undesirable fouling of critical surfaces. As surfaces become fouled with carbonaceous deposits, the efficiency of heat transfer decreases, servo controls experience hysteresis, and nozzle performance is degraded. Methods of limiting fouling include improvements in fuel thermal stability through refining techniques such as hydrotreatment and through the use of fuel additives and additive packages. Efficient fuel management for limiting fuel exposure time at temperature and surface treatment to minimize catalytic effects have also been used in efforts to minimize this problem.

Additional complications arise because of fuel management, whereby a fraction of the fuel that has already been used for cooling is directed back to on-board fuel tanks for later use. In fact, certain flight conditions such as idle descent create high heat dissipation needs at a time when combustion requirements are minimal. Under these latter conditions, most of the thermally stressed fuel is returned to the fuel tanks. As the flight progresses an increasingly larger fraction of pre-stressed fuel is utilized. Clearly, pre-stressed fuel will have reduced thermal stability. Binns and co-workers[2-5] have reported increased fouling related to recirculation of JP-8 fuels in a large-scale simulator. The present paper reports the results from a simple test simulation under well-defined isothermal test conditions at 185°C. The effects of fuel recirculation on thermal stability were determined by measurements of autoxidation behavior and surface and bulk insoluble formation for both neat fuels and recirculated blends. Potential sources of the problem are discussed, and results from the use of the JP-8+100 additive packages consisting of antioxidant, metal deactivator (MDA), and dispersant/detergent are presented.

EXPERIMENTAL

Two Jet-A fuels have been investigated; on the basis of the quantity of insolubles formed during stressing at 185°C (surface > 2.5 µg/mL; bulk > 1.8 µg/mL), these fuels have average to below-average thermal stability. Experiments were conducted at 185°C using NIFTR[6] single-pass heat exchangers. The basic experiments for deposition and oxidation measurements were described in detail previously.[7] A new recirculation configuration and related O_2 measurements will be described in more detail here. Four different types of experiments have been performed; the first two involve measurements of surface and bulk insolubles, and the last two relate to O_2 depletion. A total system pressure of 2.3 MPa was used in all experiments to ensure a single reaction phase.

Standard Single-Pass Test. Fuel, initially saturated with respect to air at room temperature, is pumped at 0.25 mL/min through stainless-steel (304) tubing (183-cm long, 0.216-cm i.d., 0.318-cm o.d.) maintained at constant wall temperature within a Cu-block heat exchanger. Because of the slow fuel flowrate, reaction occurs isothermally, and reaction time or stress duration can be calculated at each position along the tube, assuming plug flow. A complete pass through the block provides 22 min of stressing during which all of the dissolved O_2 is depleted. Fuel, after leaving the heated region, cools and passes through two in-line Ag-membrane filters (0.45 and 0.20 µm). After a 72-hr period and the passage of 1.08 L of fuel, the tube is removed, rinsed with heptane, and cut into 5.1-cm sections. Each tubing segment and filter is treated in a vacuum oven for 24 hr and then evaluated using surface-carbon analysis. The quantity of carbon in the surface insolubles is summed along the tube, and the result is expressed as total surface carbon per unit volume of fuel as a function of residence time in minutes.

Recirculation Double-Pass Test. The new test configuration (Figure 1) is a variation on the single-pass test setup whereby Pump 1 passes fuel through the heat exchanger to provide the initial stressing. After exiting the heated block, fuel is cooled for 1 min, mixed with an equal flow of unstressed fuel from Pump 2, and directed back through a second channel in the heat exchanger. The second pass simulates the use of pre-stressed (and re-oxygenated) fuel as a heat sink. Since the initially stressed fuel contains no residual O_2, the resulting blend contains 50% stressed fuel and a dissolved O_2 concentration that is 50% of the air-saturated level. At the higher flowrate (0.5 mL/min), the recirculated fuel blend receives only 11 min of stressing. At the exit of the heated block, fuel cools and passes through in-line filters. After a 72-hr period during which 1.08 L of neat fuel have passed through the first tube and 2.16 L of the pre-stressed fuel blend through the second tube, tubes and filters are evaluated for surface carbon as described above.

Autoxidation of Neat Fuel. Autoxidation occurs as fuel passes through a fixed length (81.3 cm) of heated tubing within a Cu-block heat exchanger. Reaction time within the heated tube is varied by changing the flowrate. The initial dissolved O_2 concentration is equated to 100%, and the residual dissolved O_2 following reaction is measured at the end of the tube using GC detection. In one series of experiments using reduced (50%) initial O_2 concentration, fuel is sparged for 30 min with a 1/9 blend of O_2/N_2. For reducing surface catalysis in autoxidation experiments, tubing passivated by the Silcosteel[8] process is used.

Autoxidation of Pre-Stressed Fuel. Depletion of O_2 in the recirculated blend is tracked by diverting the blended fuel into a separate heater block (81.3 cm), as shown in Figure 1, and changing the residence time by adjusting the system flowrate. These measurements are much less accurate than those discussed above for neat fuels. Through the establishment of equal, progressively higher flowrates at Pumps 1 and 2, the initial dissolved O_2 entering the second block is maintained at 50%, and reaction time in the sampling block is correspondingly reduced. Data can be collected only at flowrates where the initial fuel from Pump 1 experiences 100% O_2 conversion before blending.

RESULTS AND DISCUSSION

Surface Fouling and Autoxidation of Neat Fuel. The total surface carbon measured for neat (air-saturated) fuels is represented by closed circles in Figure 2; the corresponding autoxidation data are given in Figure 3. Autoxidation is characterized by acceleration at higher conversion caused by self-initiation from thermal--and, in addition, possible metal-catalyzed--dissociation of hydroperoxides.

Surface Fouling of Recirculated Fuel. In the current test configuration, recirculated fuel is actually a 1/1 blend of neat fuel and fuel that has been stressed for 22 min at 185°C. Since all of the O_2 has been consumed in 22 min of stressing, the resultant blend contains only 50% of the O_2 present in air-saturated fuel. In isothermal experiments with complete O_2 conversion, the total quantity of insolubles is proportional to the amount of dissolved O_2. In the absence of other factors, total surface fouling from recirculated fuel will be only about one-half that from neat fuel.

Surface fouling for recirculated-fuel blends (see Figure 2) differs significantly from that for neat fuels, although the total quantities are in the expected range. Deposition from the pre-stressed fuel blend increases sharply from $t = 0$, whereas neat fuels exhibit some delay (induction time) before the highest rate of surface fouling is achieved. Because of this difference, total fouling in the recirculation pass exceeds that of the neat fuel over at least the first 5 min of reaction. In summary, despite a reduced O_2 concentration, surface fouling in the recirculation pass occurs at shorter reaction times with a rate similar to that eventually achieved with neat fuel.

Autoxidation of Neat and Recirculated Fuels at Reduced Initial O_2. Interpretation of the deposition data requires information on the autoxidation of both neat and pre-stressed fuels at reduced initial O_2. Results of O_2 measurements are given in Figure 3. The rate of autoxidation of neat, half-air-saturated fuel is never faster than that of neat, air-saturated fuel. However, because of reduced reactant concentration, the total time required for depletion of O_2 is always less. This finding indicates that the simple reduction of dissolved O_2 associated with this test configuration cannot account for the changes in deposition observed in Figure 2. These changes result from pre-stressing.

Autoxidation of recirculated fuels requires less time than that of neat fuels, although the maximum reaction rates achieved at high conversion are similar for both the neat and recirculated fuels, independent of O_2 content. Autoxidation times of pre-stressed fuels are expected to be shorter for two reasons. The first involves depletion of antioxidants. If antioxidants are totally consumed during pre-stressing, their overall reduction in a 1/1 blend is 50%; this change alone may be sufficient to account for the observed differences. The second concerns the formation of catalytic products. It is doubtful that many hydroperoxides will survive 22 min of stressing at 185°C, but even small concentrations of dissolved metals will add to the free-radical pool.

Differences in fouling may be due only in part to oxidation. A potentially more important cause may be the presence of insolubles in the recirculated stream. Prestressing may effectively establish conditions for rapid deposition, thereby precluding the need for an induction time. This factor may account for the above observation that deposition from recirculated fuel displays little or no time delay.

Implications and Corrective Action. Two major factors are offered to account for differences in the thermal stability of neat and recirculated fuels. The first relates to increases in the rate of autoxidation caused by a combination of reduced antioxidant concentration and the formation of catalytic products. The second relates to reduction or elimination of the time delay in the formation of surface deposits. Surface fouling associated with fuel recirculation can be minimized by 1) slowing autoxidation through the use of effective primary and secondary antioxidants, 2) eliminating metal-catalyzed free-radical initiation through the introduction of a metal deactivator, and 3) reducing agglomeration of insolubles through the introduction of appropriate detergents/dispersants. The suggested methods to reduce fouling in recirculated fuel are virtually the same as those found to minimize fouling from neat fuels. Additive packages, developed as part of the USAF JP-8+100 program,[12] consisting of antioxidant, metal deactivator, and dispersant have been shown to reduce surface and bulk insolubles in both fuels studied.[9,10] Also, Binns and coworkers[2,4,5] have found reductions in surface fouling in a JP-8 fuel (POSF-2980) with the use of additive packages.

Changes in thermal stability for two candidate JP-8+100 additive packages is shown in Figure 4. In this comparison the relative change in surface fouling with the introduction of the additive package is plotted as a function of reaction time. The dashed line through the origin represents no change; positive and negative values indicate, respectively, increased and reduced fouling. Additive packages 1 and 2 differ only in the nature of the proprietary detergent/dispersant. The first is manufactured by Ethyl Corporation and the second by Betz Corporation. The two behave similarly and significantly reduce surface fouling and, by definition, improve thermal stability as measured at 185°C. Bulk insolubles are similarly reduced.

CONCLUSIONS

Small-scale isothermal rigs using only 2 L of fuel have been employed for comparing the behavior of two Jet-A fuels in a single-pass and in a recirculation test configuration to assess the effect of fuel recirculation upon thermal stability. Total insolubles collected for an extended reaction time and for complete O_2 consumption have been found to be independent of the test mode. However, recirculated fuel containing a pre-stressed fraction displays an increase in surface fouling, particularly over reduced stress times. We have identified three causes for this reduced thermal stability, all attributable to changes occurring during pre-stressing: 1) consumption of antioxidants, 2) formation of catalytic products, and 3) development of precursors to surface deposition. Changes 1) and 2) accelerate autoxidation, and change 3) reduces the delay time in surface fouling in isothermal tests. Two additive packages consisting of antioxidant, metal deactivator, and dispersant are shown to provide a simple means of reducing fouling in both single-pass and recirculation configurations. Conceivably, higher concentrations of synthetic antioxidant and dispersant may result in further reductions in fouling associated with fuel recirculation. A more detailed reporting of the effects of recirculation on these and other fuels is scheduled.[11]

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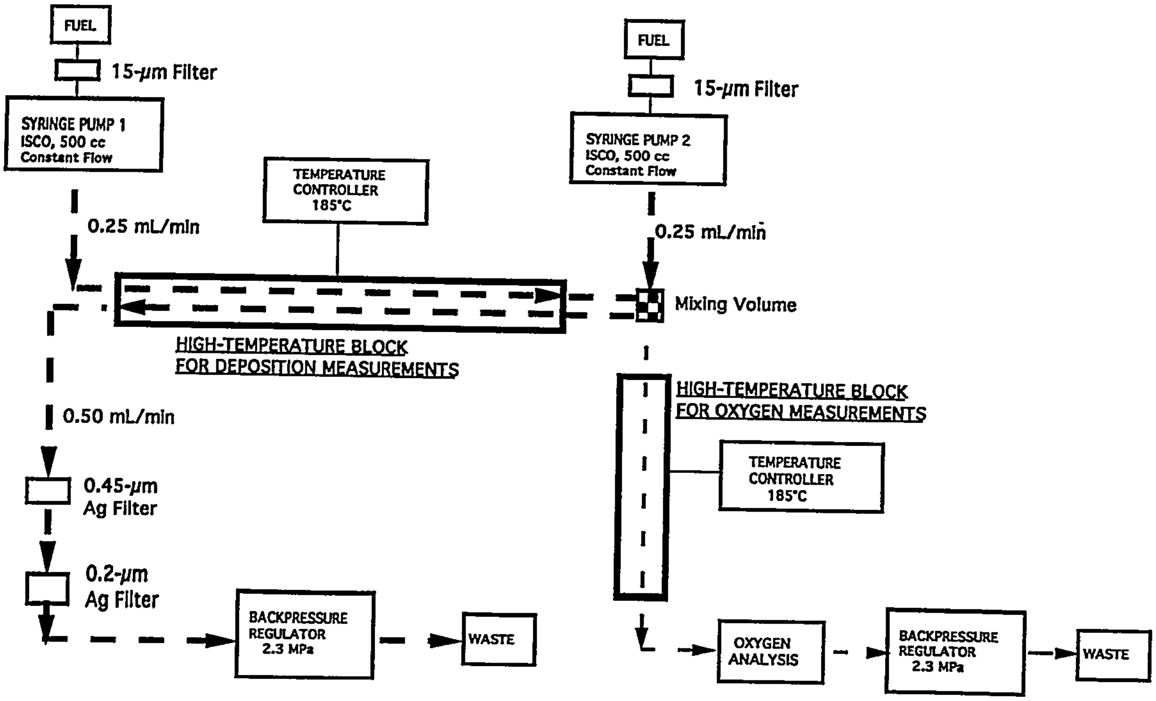

Figure 1. Schematic Diagram of Apparatus (NIFTR)

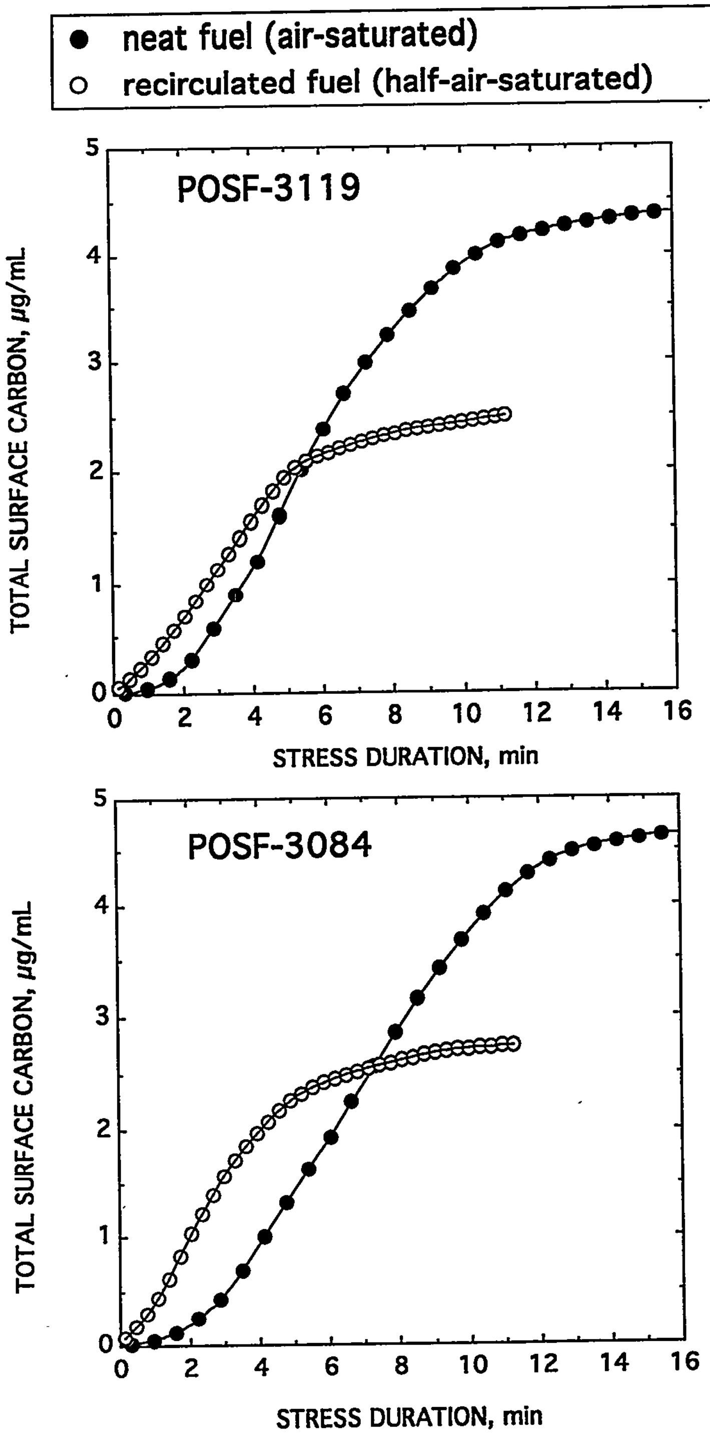

Figure 2. Surface Deposition Profiles at 185°C.

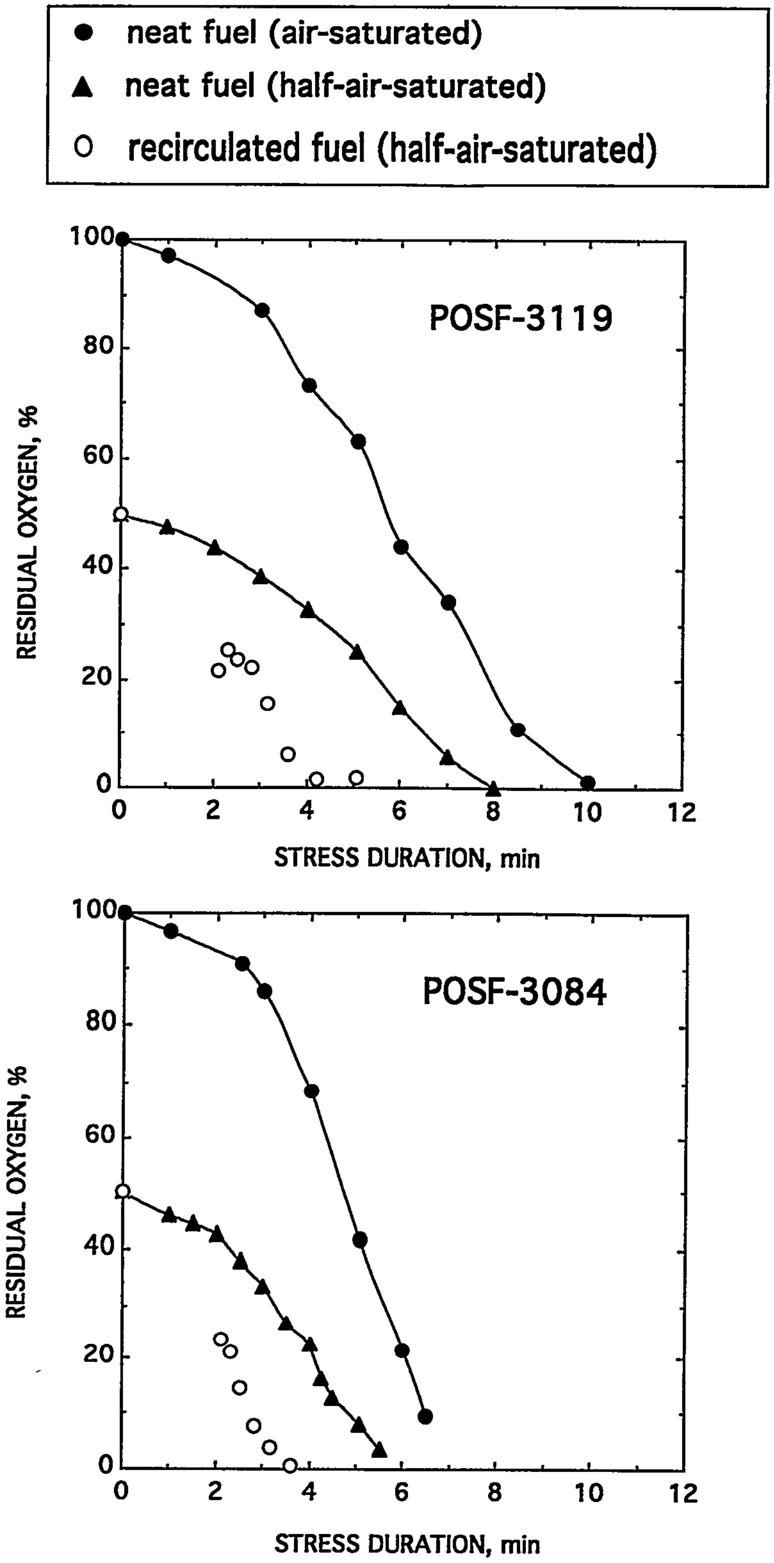

Figure 3. Autoxidation Profiles at 185°C

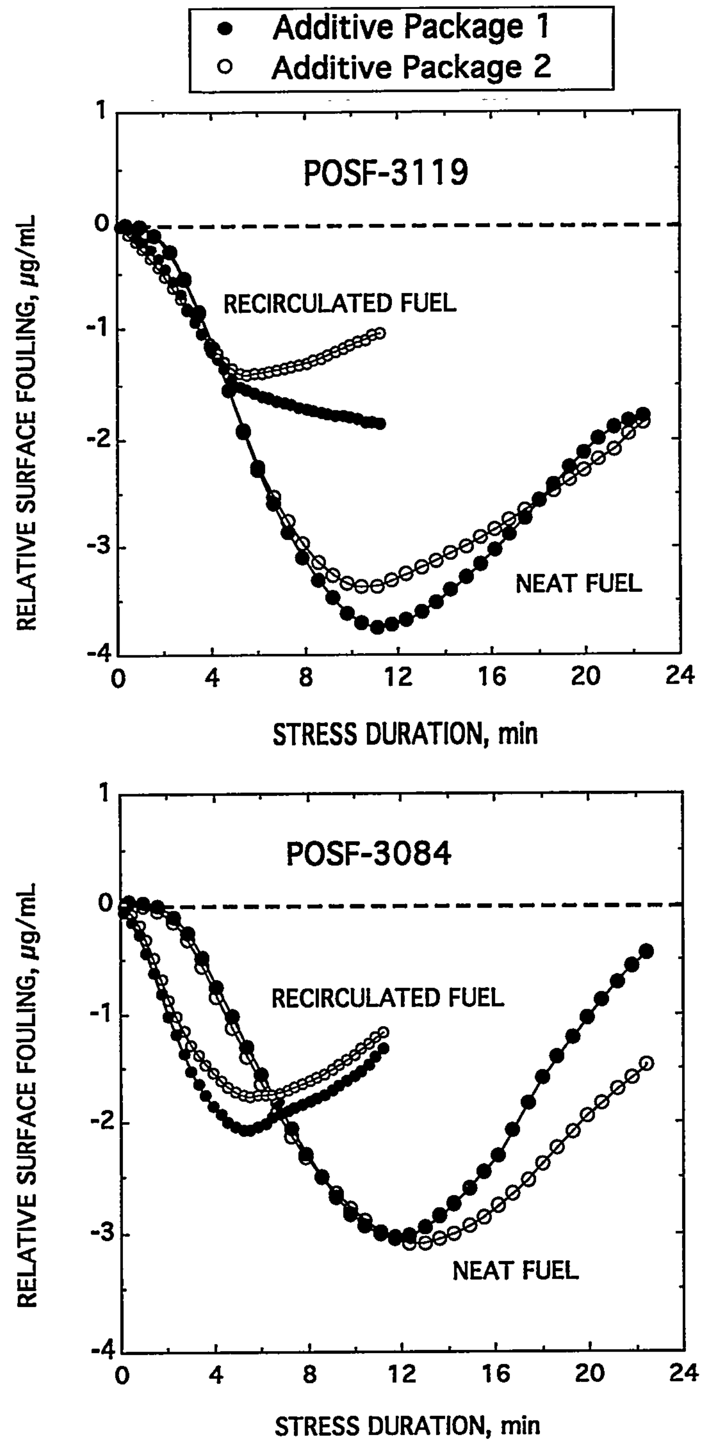

Figure 4. Effect of Additive Packages on Fouling

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COMPARISON OF THE EFFECTS OF STORAGE CONDITIONS, TYPE OF SOLUBLE COPPER, AND MDA ON JP-5 FUEL THERMAL STABILITY

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The effects of the type of storage and the source of soluble copper on fuel thermal stability were examined using five JP-5 fuels. The effects of the metal deactivator, MDA (N,N'-disalicylidene-1, 2-propane diamine) were also examined in the comparative studies using two of the five test fuels. Thermal stabilities were determined using the gravimetric JFTOT, which gives a quantitative measure of the total deposits formed. A copper concentration/storage effect was observed, which necessitated evaluations at *similar* copper concentrations. However, the source of copper appears not to be important. Instead, the main operative factor affecting the thermal stability of stored fuels appears to be the combined effect of long term ambient storage in the presence of copper. Good correlations were obtained between the thermal stabilities of fuels that were stored in the presence of 400 ppb copper from copper II ethyl acetoacetate (CuEA) at 90°C/50 psig air/24 hr versus comparable field conditions, which approximated an ambient storage period of six months in the presence of copper from 90:10 copper-nickel alloy. These results are significant for the following reasons: (1) they validate the use of the specified laboratory test conditions as being realistic; (2) they support our premise that the precursors that lead to thermal deposits are formed primarily on storage in the presence of copper; and (3) they offer a rigorous method for predicting the thermal stabilities of jet fuels. The MDA/Cu/storage studies also indicated good agreements between the thermal deposits of fuels stored using accelerated *vs* ambient conditions for periods equivalent to ~ six and twelve months in all the cases examined, which include with and without added copper from CuEA or Cu-Ni.

Introduction

Dissolved copper has been found to be the most reactive of the metals that catalyze fuel oxidation.[1,2] Consequently, due to the 90:10 copper-nickel (Cu-Ni) alloy used in the fuel piping systems of U.S. aircraft carriers and air capable ships,[3,4] copper contamination of JP-5 fuels is of particular interest to the U.S. Navy. From a commercial standpoint, copper contamination can also occur from other sources including the refinery copper sweetening process,[5] the copper bearings used in fuel pumps, and from the copper heating coils in many multipurpose tankers that are used to transport jet fuels. The adverse effects of metals, including copper, on jet fuel thermal stability have been reviewed by Nowack[6] and later by Hazlett[5] As indicated in the reviews,[5,6] the deleterious effects of copper on fuel thermal stability are dependent on the fuel and the solubilized copper concentration.

Although long term storage is pertinent to U.S. Navy fuels (JP5s), all fuels are also subject to some storage effect when one includes the time interval from the time the fuel leaves the refinery to its combustion in the aircraft. Consequently, a study of the effects of fuel storage in the presence of copper, prior to determining its thermal stability, addresses realistic conditions.

The current study is a continuation of an earlier systematic investigation,[7] the results of which indicated that precursors that lead to thermal deposits are either formed, or their formation is accelerated, when the fuel is stored in the presence of copper. In the earlier study,[7] for convenience, fuel storage was accelerated in the Low Pressure Reactor (LPR) used by Hardy *et al.*[8] and the source of copper was a fuel-soluble copper compound, viz., copper II ethyl acetoacetate (CuEA). Consequently, because of the significance of the results of the earlier study[7] it was important to validate them with respect to storage using field conditions. However, identification of the precursors formed from the autoxidation effects of the copper II cation, is a task well beyond the scope of this paper.

The *objective* of this paper is to establish that a reliable agreement exists between the thermal stabilities of fuels that have been stored in the presence of copper using laboratory test conditions versus field conditions. In this context, laboratory test conditions are defined as accelerated storage in the LPR at 90°C/50 psig air/24 and 48 hours in the presence of known concentrations of soluble copper from CuEA. Field conditions are defined as storage at room temperature (~20°C) and atmospheric pressure in the presence of known concentrations of dissolved copper from 90/10 Cu-Ni alloy for a period of approximately six and twelve months, respectively. Also, MDA was likewise examined, with and without added copper, in a limited study. Thermal stabilities of the fuels, before and after storage, were measured using the Gravimetric JFTOT.[9]

In this paper, the results of two studies on the effects of the type of storage, the source of soluble copper, and copper concentration on thermal stability are presented. In the first study, the fuel set comprised three JP -5 fuels. In the second study, the fuel set comprised two freshly refined JP-5 fuels. The purpose of the second fuel set was to validate the results of the first set. In a third study, the comparative studies were extended to include a limited probe on the effects of the metal deactivator, MDA (N,N'-disalicylidene-1,2-propane diamine), because of its well-known benefit on fuel thermal stability.[4b]

Experimental Section

Test matrix. The overall broad test matrix for the studies conducted comprised two fuel sets, two types of storage, and two sources of copper, added at two concentrations/amounts (see Table 1). Adequate design of the test matrix, with respect to copper concentration, was obfuscated due to the unpredictability of the extent of copper solubilization in the Cu-Ni alloy dissolution studies.

Materials. All materials were used as received, unless otherwise specified.
Fuels. The two fuel sets employed are designated A and B. Fuel set A comprised three fuels and were *not* the same three fuels used in our earlier study.[7] Fuel set B, comprised two fuels. The

purpose for examining a second fuel set stemmed from the unexpected high concentration of solubilized copper (~2000 ppb) obtained on exposure of the fuels in set A, to Cu-Ni alloy.

As shown in Table 2, based on some pertinent compositional and properties data, the neat test fuels can be categorized as typical JP-5 field production jet fuels.[10] The inherent copper contents of the neat test fuels ranged from negligible (fuel set B: 2-4 ppb) to low (fuel set A: 18-22 ppb). Each fuel was obtained from a different location/refinery and for convenience they are thus identified. The three fuels included in set A are: Pax River (from Patuxent River Naval Air Station, VA), Norfolk (from the Defense Distribution Depot, in Norfolk, VA), and NAWC (from the Naval Air Warfare Center in Trenton, NJ). The two fuels included in set B are: TX from Texas and LA from Louisiana.

Copper. The two sources of copper used and the respective concentrations/amounts for the fuel sets employed are as follows:
(a) *copper II ethyl acetoacetate* (CuEA) from Eastman Kodak. For fuel set A, the copper concentration of CuEA initially employed for both the room temperature and accelerated storage studies was 400 ppb. This level was chosen because it depicts a median level of the range[5] in copper concentration found in JP-5 fuels aboard the U.S. Navy aircraft carriers. Significantly higher levels (1700-2000 ppb) were also examined in the LPR, to match the high levels of solubilized copper from the Cu-Ni alloy/room temperature storage studies. And, to validate the thermal stability results obtained from the fuels in set A, for fuel set B, the copper concentrations of CuEA employed were 400 and 2000 ppb in both the accelerated and room temperature storage studies.

(b) *90/10 copper/nickel alloy* from Hillman Brass and Copper Co. For fuel set A, the Cu-Ni alloy used was in the form of plates. The dimensions of each plate were: 7 cm x 10 cm x ~ 0.15 cm; ten plates were used per test fuel. For fuel set B, the alloy was used in the form of rods to facilitate mixing (see Procedures, Stirring). The dimensions of each rod were: 2.54 cm x 0.95 cm diameter. In an effort to obtain different concentrations of solubilized copper, six and eighteen rods were used.

N,N'-disalicylidene-1,2-propane diamine commonly known as MDA was obtained as a powder from Pfaltz and Bauer. In a limited study, MDA was added at 20 and 40 ppm concentrations to each fuel in set B (i.e., TX and LA).

Procedures

Pretreatment. The copper-nickel alloy plates and rods were cleaned by first immersing in a mixture of equal volumes of toluene, acetone, and methanol, then rinsed with hexane, and air dried.

Stirring. The copper-nickel plates were held in wedges made in a Teflon rack that was constructed from two parallel placed Teflon strips (13 cm x 1.5 cm x 0.5 cm). Teflon beading obtained from Atlantic Tubing Co., was threaded through holes bored near the ends of the rack, and used for suspension purposes. This facilitated periodic stirring of the fuel by manually rotating the rack, which housed the copper plates. Rods were used in the second fuel set instead of plates to simplify mixing, which was effected simply by shaking the capped cans. Otherwise throughout storage, the epoxy coated one-gallon cans containing the test fuels were either loosely covered with aluminum foil (when plates were used), or covered with foil pierced with small holes for aeration purposes (when rods were used).

Copper analyses. The concentrations of fuel solubilized copper from the Cu-Ni alloy/room temperature storage studies were determined at periodic intervals. Copper analyses were performed using graphite furnace atomic absorption spectroscopy, at the Naval Air Warfare Center, Aircraft Division, Trenton, NJ.

Fuel storage. The two forms of storage used were: (1) at room temperature (approximately 20°C) and atmospheric pressure, hereafter referred to simply as ambient storage; and (2) accelerated storage, which was conducted at 90°C under a pressure of 50 psig air for 24 and 48 hours in a Low Pressure Reactor (LPR).[8] The accelerated conditions of 90°C/50 psig air/24 and 48 hours were intended to simulate room temperature storage for approximately six and twelve months, respectively.

Gravimetric JFTOT. Thermal stabilities of the fuels, before and after storage, were measured using the gravimetric JFTOT.[9] This method gives the weight of total thermal deposits formed, in mg/L, when a fuel flowing at 3 mL/min is heated at 260°C, under approximately 500 psi back pressure, for 2.5 hr. The filtered fuel flows over a stainless steel strip (grade 302 and approximately 7 cm x 0.5 cm x 0.025 mm), contained in a heated strip holder. The total deposit is the sum of the deposits formed on the stainless steel strip and the filterables contained in the effluent. The effluent was filtered using two Magna nylon membranes of 0.8 micron pore size. Further details of the method are described elsewhere.[7,9] In the gravimetric JFTOT method, the strip deposits are significantly lower than the filterables: on average, about 10% of the total weight. And, because the strip deposits track well with changes in the filterables, only the *total* thermal deposits are reported (Tables 3-9).

Repeatability. Thermal stability determinations of the room temperature-stored fuels were conducted in duplicate. The overall repeatability of the duplicate testings was within the average standard error (standard deviation estimate x 100/mean), which is approximately ±15% for the total thermal deposits in the gravimetric JFTOT. Duplicate determinations of the accelerated stored fuels were generally not done since earlier studies had indicated the repeatability had no subsequent effect on thermal stability tests.

Results and Discussion

Copper/Storage: Studies 1 and 2

Neat fuels. Based on the criterion by Hardy *et al.*,[11] that for stable fuels the maximum total deposit is 5 mg/L, the five test fuels may be described as thermally stable. For example, as shown in Tables 3 and 4, low total thermal deposits (approximately 0.1-0.9 mg/L) were formed from the individual effects of storage, and of added copper, *as well as* from their combined effects, e.g., on storage in the presence of 400 ppb copper, the total deposits formed were approximately 0.6-3 mg/L (Table 4).

Effects Compared. The effects of accelerated *vs* room temperature storage on the thermal stabilities of the stored fuels were compared for storage conducted without and with added copper. When the source of added copper was CuEA, the effects of accelerated *vs* room temperature storage on fuel thermal stability were compared at similar copper concentrations. However, when the source of added copper was Cu-Ni, the effects of storage - using laboratory test conditions (accelerated storage: 24 hr LPR in the presence of CuEA) *vs* field conditions (storage at room temperature and pressure in the presence of 90:10 Cu-Ni for approximately six months) also at similar copper concentrations - on fuel thermal stability were determined (see Fuel storage using laboratory test *vs* field conditions).

Approximate Six Months Ambient Storage Period versus 24 hr LPR (90°C/50 psig air)

Fuel storage only: no copper added (Table 3). Both fuel sets exhibited good agreements between the thermal stabilities of the fuels stored at accelerated conditions (24 hr LPR) versus those stored at room temperature for approximately six months. The agreements are considered to be good because large percentage differences for such small amounts of deposits are not meaningful (i.e., compared to the maximum of 5 mg/L for stable fuels[11]).

Fuel storage in the presence of CuEA (Table 4):
At 400 ppb copper from CuEA, when one factors in the repeatability of the gravimetric JFTOT test method, the overall results for the five test fuels again indicate good agreements between the thermal stabilities of the accelerated and the room temperature stored CuEA additized fuels.

At 2000 ppb copper from CuEA, comparisons are pertinent only to fuel set B (see test matrix, Table 1). Of the two fuels in set B only the LA fuel exhibited good agreement between the thermal stabilities of the accelerated and room temperature stored CuEA fuels.

Fuel solubilization of copper from the Cu-Ni alloy ambient storage studies (Figures 1 and 2). In general, all the test fuels showed increases in copper levels with time, which were followed by a decrease. For the TX fuel (Figure 2), this trend is not apparent graphically because of the wide range in the scale of the ordinate. However, the extent of the increases, with time, differed significantly with the fuel, thereby suggesting a fuel dependency. For the fuels in set A (Figure 1), the maximum appears at ~2000-2400 ppb copper; whereas, for the fuels in set B (Figure 2), the maximum appears at approximately 100 ppb for the TX fuel, and at approximately 3500 ppb for the LA fuel.

Fuel storage using laboratory test vs field conditions (Table 5). The concentrations of solubilized copper from the Cu-Ni/room temperature storage studies differed significantly from the concentrations of soluble copper added as CuEA in the storage studies conducted. Due to a copper concentration effect that was identified (see Copper concentration/storage effect), these significant concentration differences necessitated comparisons of the thermal stabilities of the stored fuels at *similar* copper concentrations. Consequently, direct comparisons between laboratory test versus field conditions were limited. Subject to the available data, direct comparisons at copper concentrations of approximately 400 ppb and 2000 ppb are subsequently described.

At ~400 ppb copper from Cu-Ni:

For fuel set A, the significantly high solubilized copper concentrations after approximately six months storage at room temperature (viz., 1800-2200 ppb, Figure 1) preclude a direct comparison between the thermal stabilities of fuels stored using laboratory test *vs* field conditions in the presence of 400 ppb copper. Nevertheless, an evaluation based on an indirect comparison is addressed later (see Evaluation of the Thermal Stabilities of Fuels Stored Under Laboratory *vs* Field Conditions).

For fuel set B, with respect to the extent of copper solubilization after approximately six months storage at room temperature, the converse effect was observed: the solubilized copper levels were considerably lower. For example, in the presence of six Cu-Ni rods, the copper levels were 70 and 169 ppb for the TX and LA fuels, respectively. In the presence of 18 Cu-Ni rods, the copper levels were 108 and 455 ppb, respectively.

Nevertheless, as shown in Table 5, for fuel set B, good agreements are exhibited between the thermal stabilities of the fuels that were stored using laboratory test conditions in the presence of 400 ppb copper from CuEA versus those stored using field conditions in the presence of approximately 100-400 ppb from Cu-Ni. The agreements are considered to be good based on their similarly small amounts of thermal deposits. The improved agreements at the higher levels of solubilized copper (cf. data for 6 *vs* 18 Cu-Ni rods) suggest that a threshold concentration effect may also be operative.

At ~ 2000 ppb copper from Cu-Ni. At this high level of solubilized copper from Cu-Ni, direct comparisons are applicable only to the fuels in set A (see Table 5). And, of the three fuels in this set, two (viz., Pax River and Norfolk) exhibited good agreements in their thermal stabilities on storage in the presence of similarly high concentrations of copper (~2000 ppb) using laboratory conditions (CuEA copper-doped/24 hr LPR accelerated storage) versus field conditions (Cu-Ni/6-7 months room temperature storage). The corresponding correlation for the NAWC fuel may be considered to be reasonable when one factors in the ±15% repeatability of the test method: on doing so, the total thermal deposits for the LPR stored fuel becomes 6 mg/L and for the room temperature stored fuel, 5 mg/L.

Twelve-Fourteen Months Ambient Storage Period versus 48 hr LPR (90°C/50 psig air)

On extended storage (Table 6), for the non copper doped fuels in set A, good correlations were obtained between the thermal stabilities of fuels that were stored using accelerated versus ambient conditions. Corresponding correlations for fuels that were stored in the presence of copper were consistently poor for all fuels in set A and for one of the two fuels in set B. For example, for fuel set B, when one factors in the repeatability of the test method, only the LA fuel exhibited correspondingly good correlations in all the cases examined.

Factors that Impact on the Analysis of the Results

The objective of this study was to determine whether the thermal stabilities of fuels that were stored using laboratory test conditions were similar to those stored using field conditions. Complicating the analysis of the results is the copper concentration/storage effect that appears to be operative for these fuels. This effect as well as the source of copper/storage effect on total thermal deposits are discussed subsequently. Both these factors are discussed prior to evaluating the results obtained, because they are pertinent to, and impact on, the analyses of the data.

Copper concentration/storage effect. Although the effect of copper is reported to be catalytic,[5,12] increases in concentrations at low copper levels have been known to increase thermal deposits.[5] For the fuels examined, increases in total thermal deposits due to a combined copper concentration/storage effect are shown in Table 7. For example, the total thermal deposits of most of the fuels increased with increasing concentrations of added copper from CuEA, regardless of the type of storage. The increases in thermal deposits for the fuels in set A, and particularly so for the Pax River fuel - on storage in the presence of approximately 2000 ppb copper, from Cu-Ni plates, versus storage in the presence of 400 ppb copper from CuEA - are likely attributable to a copper concentration effect and not to the difference in the source of soluble copper used (see Copper source, below).

Note: For the fuels in set B, relative to the concentration effect at 2000 ppb *vs* 400 ppb copper from CuEA (Table 7), the concentration effect at 400 ppb *vs* 100 ppb copper from Cu-Ni is relatively small (see Table 5). This is likely attributable to the inherent thermal stabilities of the neat fuels, i.e., such stable fuels likely exhibit a higher copper concentration threshold effect in the copper promoted autoxidation reactions of jet fuels.

Copper source/storage effect. The *source* of copper does not appear to play a role in the thermal stabilities of fuels that were stored in the presence of copper. Supporting this premise are the similar amounts of total thermal deposits formed from both fuels in fuel set B (Table 8), after storage at room temperature, in the presence of approximately 100-400 ppb copper, whether copper was derived from CuEA or from Cu-Ni rods. Furthermore, the reasonable to good agreements obtained between the thermal stabilities of the fuels in set A that were stored in the presence of approximately 2000 ppb copper, using laboratory test versus field conditions (Table 8), suggest the following: based on the specific test matrix examined, it is the combined effect of storage in the presence of copper that is important, and not the type of soluble copper, nor the type of storage.

Based on the above results, the anion of the copper II compound in these tests (viz., ethyl acetoacetate in the case of CuEA, or possibly one derived from the organic acids present in the fuel, as would be the case for Cu-Ni alloy), does not appear to participate in the reactions that lead to thermal deposits. From an autoxidation aspect (see Role of copper, below), this interpretation is consistent with Morris[13] and Turner's results that the source of the anion in the copper compound appears not to be a factor in oxygen consumption. These overall results do not support

Datschefski[14] findings that, in addition to the copper concentration, the chemical structure of the dissolved copper compound is also important.

Role of copper. Copper is reported to catalyze the formation of thermal deposits via the initiation of free radicals during the autoxidation process.[12] Also, being a multivalent ion, copper likely plays a role in the decomposition of hydroperoxides formed from the free radicals.[15] Nevertheless, the copper concentration effect observed, focuses on the threshold level of copper being fuel dependent.[6]

Test matrix design. The amounts of copper that a particular fuel will dissolve under a given set of conditions from contact with Cu-Ni alloy on storage at room temperature appear to be dependent on the fuel, the copper surface area/fuel volume, and the length of storage (see Figures 1 and 2). Consequently, it is inherently difficult to adequately design the test matrix with respect to copper concentration. Furthermore, the unpredictability of the extent of copper dissolution from Cu-Ni alloy becomes a particularly significant factor due to the copper concentration effect that appears to be operative for these fuels.

Evaluation of the Thermal Stabilities of Fuels Stored Under Laboratory *vs* Field Conditions

400 ppb Copper/storage (equivalent to ~6 months at room temperature)
For the fuels in set A, the solubilized copper concentrations from Cu-Ni (~2000 ppb, see Figure 1), were significantly higher than the 400 ppb soluble copper from CuEA used in the accelerated storage studies. In the effort to compare the thermal stabilities of fuels that were stored using laboratory test *vs* field conditions in the presence of 400 ppb copper, we adopted the following indirect method of analysis:

First, we compared the total thermal deposits formed from the fuels that were stored in the presence of 400 ppb copper from CuEA using accelerated versus room temperature conditions equivalent to approximately six months storage (Table 4). Since these showed good agreement, we then examined the effect of the source of copper. And, as discussed earlier, since the source of copper appears not to be important, we conclude that, at 400 ppb, as at 2000 ppb copper, the fuels in set A exhibit good agreement among the thermal stabilities of the stored fuels, regardless of the source of copper or the type of storage, when the storage period is equivalent to six months at room temperature conditions.

For fuel set B, this indirect mode of analysis was not required. As mentioned earlier, both fuels in set B exhibited good agreements, i.e., between the thermal stabilities of fuels stored in the presence of 100-400 ppb copper, using laboratory test versus field conditions (Table 5).

Thus, based on direct and indirect modes of comparisons, the overall good agreements for all five typical JP-5 test fuels examined, validate the use of specified laboratory test conditions (90°C/50 psig air/24 hrs in the presence of 400 ppb copper from CuEA) as being representative of storage under specified field conditions (six months' storage at room temperature in the presence of copper from Cu-Ni at similar copper levels). Furthermore, accelerated storage of the test fuels using these validated laboratory test conditions, prior to determining their thermal stabilities can further serve as a rigorous predictive test method for assessing the potential thermal stabilities of jet fuels.

2000 ppb Copper/storage (equivalent to ~6 months at room temperature)

The reasonable and good agreements in the thermal deposits obtained for the fuels in set A, when stored in the presence of approximately 2000 ppb copper, using laboratory test versus field conditions (Table 5), would have been particularly useful when designing a predictive test for differentiating fuel thermal stability because of the copper concentration effect. However, the relatively poor correlation in the thermal deposits of the TX fuel for storage conducted using accelerated *vs* ambient conditions at similarly high copper levels from CuEA (see Table 4) suggests a fuel dependency and consequently would not be advisable for such high copper levels. Nonetheless, because copper levels as high as 1200 ppb have been reported in JP-5 fuels aboard U.S. Navy aircraft carriers[3] it may be worthwhile to conduct further studies at 1000 ppb copper to establish the optimum copper concentration for predictive test purposes.

Storage conditions

Correlations between the thermal stabilities of fuels that were stored in the presence of similar copper concentrations, using laboratory versus field conditions, were good when the storage period was equivalent to approximately six months at ambient conditions. However, when storage was extended to a period equivalent to approximately one year (12-14 months) at ambient conditions, the corresponding correlations were poor. As shown in Table 6, for fuel set A (no comparable data available for fuel set B), the consistent significantly higher amount of thermal deposits formed - on accelerated storage in the presence of 2000 ppb copper from CuEA for 48 hr in the LPR *versus* ambient storage for 12-14 months in the presence of similar concentration of copper from copper-nickel - may well be attributable to a time/ temperature effect.

Copper concentration effect versus accelerated stress time

For the fuels in set A, the significantly greater amount of deposits formed - on accelerated storage in the presence of 400 ppb copper for 48 hours (Table 6) versus 1700 ppb copper for 24 hours (Table 4) - suggests that of the two effects, stress time is more dominant, and unrealistically so, due to the time/temperature effect mentioned above.

Precursors' formation on storage in the presence of copper

The good agreements in the thermal deposits of the test fuels that were stored using the specified laboratory *vs* field conditions, support our original premise[7] that precursors that lead to thermal deposits are primarily formed, or their formation is accelerated, on long term ambient storage in the presence of copper. In this study, this is exemplified by the increases in thermal deposits due to the interactive effects of storage in the presence of copper, relative to the individual effects of storage and of copper (see Table 7). However, the small magnitude of the increases due to the combined effects, e.g., storage in the presence of 400 ppb copper, versus the individual effects (copper only, or storage only), likely reflects the inherent thermal stabilities of the neat fuels.

MDA/Copper/Storage: Study 3

Fuel set B. Because of the limited quantity of available freshly refined fuels, the MDA studies conducted are based on a judicious design of the test matrix. The total thermal deposits of the fuels that were stored in the presence of MDA and added copper from either CuEA or Cu-Ni, in the studies conducted, are shown in Table 9. And, to evaluate the effects of MDA on fuel thermal stability for the test matrix examined, the total thermal deposit data of the corresponding neat, stored, and copper-doped stored fuels - with no MDA present - are also included in Table 9.

As shown in Table 9, both fuels in set B exhibited excellent agreements in the thermal stabilities of the test fuels that were stored in the presence of MDA in all the cases examined. These include the following:

(a) with and without added copper (one case was examined with no added copper).
(b) using accelerated *vs* ambient conditions.
(c) using laboratory test *vs* field conditions (one case examined, viz.,for storage period equivalent to approximately 12-14 months at ambient conditions).
(c) for storage periods equivalent to approximately 6 months (one case examined) and 12-14 months at ambient conditions.

The results also indicate that MDA consistently improved the thermal stabilities of the fuels that were stored in the presence of copper ranging from100-2700 ppb concentrations in conjunction with high concentrations of MDA (20 and 40 ppm). However, because of the overall stabilities of the neat test fuels, the improvements were generally not dramatic except in one case. Specifically, MDA significantly decreased the thermal deposits of the TX fuel that was stored in the presence of 2000 ppb copper *and* 40 ppm MDA for approximately 14 months at ambient conditions (cf., 0.5 mg/L versus 21 mg/L total thermal deposits, for the corresponding copper doped/no MDA/stored fuel). Also, for the *non-copper doped* 12-14 month stored fuels, at the high concentration employed (20 ppm), MDA was not detrimental. This evaluation is based on the rationale, described earlier, that large percentage differences of small amount of deposits are not meaningful.

Conclusions

A copper concentration effect was identified which necessitated evaluations at fairly similar copper concentrations. Based on direct and indirect modes of analyses, all five typical JP-5 field production test fuels exhibited good agreements in their thermal stabilities for fuels that were stored - with and without added copper - using specified laboratory test versus field conditions equivalent to six months ambient storage. Consequently, the specified laboratory test conditions, viz., accelerated storage at 90°C/50 psig air/24 hr in the presence of 400 ppb copper from copper II ethyl acetoacetate, simulate field storage conditions of approximately six months at room temperature in the presence of similar amounts of copper derived from 90:10 Cu-Ni alloy.

The MDA/Cu/storage studies also indicated good agreements between the thermal deposits of the fuels that were stored using accelerated *vs* ambient conditions, in all the cases examined.

These include storage in the presence of MDA with and without added copper from either CuEA or Cu-Ni for periods equivalent to approximately six and twelve months at ambient conditions.

The overall results further indicate that whereas the source of soluble copper does not appear to be important in the test matrix examined, the main operative factor appears to be the combined effect of long term ambient storage in the presence of copper. These results thus support our original premise that precursors that lead to thermal deposits are primarily formed, or their formation is accelerated, when copper is present during storage.

The increase in thermal deposits attributable to the combined copper concentration/storage effect is particularly relevant in designing a predictive test method for differentiating the thermal stabilities of jet fuels and needs to be explored further in future studies, i.e., accelerated storage of the fuel in the presence of copper prior to the determination of its thermal stability. Moreover, based on the variables examined in this study, interested users can construct laboratory conditions to reflect their own field conditions.

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Table 1. Summary of the Test Matrix for the Three Studies Conducted

test matrix*	Cu/storage**		Cu/MDA/storage***
	study 1	*study 2*	study 3
fuel set: JP-5 fuels	A: Pax River, Norfolk, NAWC	B#: TX, LA	B#: TX, LA
CuEA,ppb: 24,48 hr LPR	400, 1700-2000	400, 2000	400, 2000
: ˜6,12 mth Amb	400	400, 2000	400, 2000
90:10 Cu-Ni: Amb	10 plates	6,18 rods	6, 18 rods
MDA, ppm	nd	nd	20, 40

* LPR: accelerated storage using a low pressure reactor; Amb: ambient storage

** Storage in the presence of copper. The type of storage and the source of copper is, as identified; nd: not determined.

*** Storage in the presence of copper and MDA, as identified.

\# Fuels were freshly refined.

Table 2. Available Properties and Compositional Data for Four Fuels Examined*

properties/composition (ASTM method, MIL-T- 5624 specification limits)	**Norfolk**	**NAWC**	**TX**	**LA**
aromatics, vol% (D1319, max: 25)	16	19.6	19	14.9
olefin, vol% (D1319, max: 5)	1.1	1.7	0.8	1.1
mercaptan sulfur, wt% (D3227, max: 0.0020)	0.0011	- ve**	0.0001	0.0012
total sulfur, wt% (D4294, max: 0.40)	0.07	0.06	0.0069	0.09
total acid, mg KOH/g (D3242, max:0.015)	0.002	0.009	0.003	0.002
density, g/mL (D4052, min-max: 0.788 - 0.845)	0.818	0.811	na	0.819
flash point, °C (D93, min: 60)	64.4	67	62.2	64
freeze point, °C (D2386, max: - 46)	- 48	- 50	- 50.5	- 48.5
peroxide content, ppm (D3703, max: 8)	<0.001	na	<0.001	<0.001
antioxidant	✓	✓	✓	✓
corrosion inhibitor	✓	✓	✓	✓
fuel system icing inhibitor, vol% (0.15-0.20)	0.17	0.14	0.13	not stated
copper content, ppb	22	19	4	2

* Corresponding data for the Pax River fuel were not available; however its copper content was 18 ppb; na: not available.

** Based on Doctor test.

✓: added

Table 3. Effects of theType of Storage/No Added Copper on Total Thermal Deposits
Comparison of Accelerated vs Ambient Storage

test description	grav. JFTOT total deposit (mg/L)				
	fuel set A			***fuel set B***	
	PXRVR	NFLK	NAWC	TX	LA
neat: (reference)	0.1	0.5	0.1	0.3	0.3
accelerated storage (24 hr LPR)	0.2	0.6	0.2	0.3	0.5
ambient storage (~6 months)	0.4	0.9	0.7	0.2	0.4

Table 4. Effects of Storage in the Presence of Soluble Copper from CuEA
Comparison of the Type of Storage at Similar Copper Concentration on Total Thermal Deposits

test description	grav. JFTOT total deposit (mg/L)				
	fuel set A			***fuel set B***	
	PXRVR	NFLK	NAWC	TX	LA
neat (reference)	0.1	0.5	0.1	0.3	0.3
~400 ppb Cu(CuEA)/no storage	0.1	0.3	0.5	nd	nd
at ~400 ppb Cu as CuEA					
accelerated storage (24 hr LPR)	0.9	3.1	2.0	0.6	1.6
ambient storage (~6 months)	0.6	1.7	2.8	0.8	1.2
at ~1700-2000 ppb Cu as CuEA					
accelerated storage (24 hr LPR)	5.0	4.2	7.0	6.2	4.4
room temp storage (~6 months)	nd*	nd	nd	2.9	3.3

* nd: not determined.

Table 5. Effects of Storage Using Lab vs Field Conditions on Total Thermal Deposits

Comparison of CuEA/Accelerated Storage vs Cu-Ni/Room Temperature Storage at Similar Copper Concentrations

test description	grav. JFTOT total deposit (mg/L)				
	fuel set A			***fuel set B***	
	PXRVR	NFLK	NAWC	TX	LA
neat (reference)	0.1	0.5	0.1	0.3	0.3
~400 ppb Cu(CuEA)/no storage	0.1	0.3	0.5	nd *	nd
at ~100-400 ppb Cu:					
lab test condns: 24 hr LPR/CuEA: 400 ppb Cu	0.9	3.1	2.0	0.6	1.6
field condns: ~6 mths rm temp/(6 Cu-Ni rods): ~70 and 169 ppb Cu**	nd	nd	nd	0.4	1.0
field condns: ~6 mths rm temp/(18 Cu-Ni rods): ~108 and 455 ppb Cu**	nd	nd	nd	0.7	1.5
at ~1700-2300 ppb Cu#:					
lab test condns: 24 hr LPR/ CuEA: 1700-2000 ppb Cu	5.0	4.2	7.0	6.2	4.4
field condns: ~ 6 mths rm temp/Cu-Ni plates: 1900-2300 ppb Cu	4.3	4.8	4.2	nd	nd

* nd: not determined.

** the first Cu concentration pertains to the TX fuel, and the second, to the LA fuel.

\# range of added/solubilized copper levels for the test fuels as specified.

Table 6. For Storage Equivalent to ~ 12-14 months Ambient

Comparison of the Effects of Type of Storage and Soluble Copper on Thermal Stability

test description	grav. JFTOT total deposit (mg/L)				
	fuel set A			*fuel set B*	
	PX RVR	NFLK	NAWC	TX	LA
neat: no storage (reference)	0.1	0.5	0.1	0.3	0.3
storage only (12-14 mths ambient):					
accelerated (LPR)	0.3	2.1	1.1	nd	nd
ambient (amb)	0.1	0.8	0.6	0.2	0.4
~100-400 ppb Cu and above/storage:					
~400 ppb Cu (CuEA)/LPR	10.4	7.3	7.1	6.6	2.7
~400 pb Cu (CuEA)/Amb	0.4	2.5	3.3	0.6	2.3
100 and 1690 ppb Cu* (6 Cu-Ni rods)/Amb	nd	nd	nd	0.7	2.8
~2000 ppb Cu/storage:					
~2000 ppb Cu (CuEA)/LPR	14.6	7.2	10.4	nd	nd
2000 ppb Cu (CuEA)/Amb	nd#	nd	nd	21.1	3.5
~2000 and 2730 ppb Cu**(Cu-Ni)/Amb	3.2	4.1	4.7	na##	5.3

* the first Cu concentration pertains to the TX fuel and the second, to the LA fuel.

** the first Cu concentration pertains to the fuels in set A and the second, to the LA fuel in set B.

\# nd: not determined.

\## na: not applicable - the solubilized Cu concentration for the TX fuel was 210 ppb, which is significantly lower than the ~ 2000 ppb Cu solubilized by the other test fuels.

Table 7. Effect of Copper Concentration/Storage on Total Thermal Deposits

test description	grav. JFTOT total deposit (mg/L)				
	fuel set A			***fuel set B***	
	PX RVR	NFLK	NAWC	TX	LA
<u>added copper as CuEA/accelerated storage (24 hr LPR)</u>					
neat fuel: no storage/no added Cu (reference)	0.1	0.5	0.1	0.3	0.3
storage/no added Cu	0.2	0.6	0.2	0.3	0.5
~ 400 ppb Cu	0.9	3.1	2.0	0.6	1.6
1700-2000 ppb Cu	5.0	4.2	7.0	6.2	4.4
<u>added copper as CuEA or Cu-Ni/room temp storage/~6 mths</u>					
no added Cu	0.4	0.9	0.7	0.2	0.4
~ 400 pb Cu (CuEA)	0.6	1.7	2.8	0.8	1.2
1700-2000 ppb Cu (CuEA)	nd *	nd	nd	2.9	3.3
1900- 2300 ppb Cu: Cu/Ni plates	4.3	4.8	4.2	nd	nd

* nd: not determined.

Table 8. Effect of Source of Copper/Storage on Total Thermal Deposits

At Fairly Similar Copper Concentrations

test description	grav. JFTOT total deposit (mg/L)				
	fuel set A			***fuel set B***	
	PX RVR	NFLK	NAWC	TX	LA
<u>~100-400 ppb Cu/type of storage</u>					
~ 400 ppb Cu (CuEA)/room temp storage	0.6	1.7	2.8	0.8	1.2
108 and 455 ppb Cu** (18 Cu-Ni rods)/room temp storage	nd *	nd	nd	0.7	1.5
<u>~1700-2300 ppb Cu#/ type of storage:</u>					
1700-2000 ppb Cu (CuEA)/accelerated storage (lab)	5.0	4.2	7.0	6.2	4.4
1900- 2300 ppb Cu (Cu-Ni plates)/room temp storage (field)	4.3	4.8	4.2	nd	nd

* nd: not determined.

** the first copper concentration pertains to the TX fuel and the second, to the LA fuel

range of added/solubilized copper levels for the test fuels as shown.

Table 9. Limited Comparison of the Effects of MDA, the Type of Storage, and Soluble Copper on Thermal Stability For Two Typical JP-5 Fuels

test description *	grav. JFTOT total deposit (mg/L) *fuel set B* TX	LA
<u>*Storage: approx 6 months ambient/24 hr LPR*</u>		
neat: no storage	0.3	0.3
LPR	0.3	0.5
ambient storage	0.2	0.4
<u>*storage/~2000 ppbCu:*</u>		
2000 ppb Cu (CuEA)/LPR	6.2	4.4
1700-2000 ppb Cu (CuEA)/Amb	2.9	3.3
<u>*storage/~2000 ppbCu/MDA:*</u>		
2000 ppb Cu (CuEA)+ 40 ppm MDA/LPR	0.3	0.7
1500-1870 ppb Cu (CuEA)+ 40 ppm MDA/Amb	0.2	1.1
<u>*Storage: approx 12-14 months ambient/48 hr LPR*</u>		
ambient	0.2	0.4
<u>*storage/MDA (no Cu)*</u>		
20 ppm MDA/LPR	0.2	0.1
20 ppm MDA/Amb	0.3	0.1
<u>*storage/~400 ppbCu:*</u>		
398 ppb Cu (CuEA)/LPR	6.6	2.7
400 ppb Cu (CuEA)/Amb	0.6	2.3
75 and 2170 ppb Cu (6 Cu-Ni rods)/Amb	0.7	2.8
<u>*storage/~400 ppbCu/MDA:*</u>		
398 ppb Cu (CuEA) +20ppm MDA/LPR (lab conditions)	0.2	0.2
400 ppb Cu (CuEA)+ 20 ppm MDA/Amb	0.1	0.5
480 and 260 ppb Cu (6 Cu-Ni rods) + 20 ppm MDA/Amb (field conditions)	0.2	0.6
<u>*storage/~2000 ppbCu or as indicated:*</u>		
2000 ppb Cu (CuEA)/Amb	21.1	3.5
210 and 2730 ppb Cu (18 Cu-Ni rods)/Amb	0.5	5.3
<u>*storage/~2000 ppbCu/MDA:*</u>		
2000 ppb Cu (CuEA) + 40 ppm MDA/Amb	0.5	0.9
2090 and 1540 ppb Cu (18 Cu-Ni rods) + 40 ppm MDA/Amb	0.3	1.1

*Where two Cu concentrations are given, the first pertains to the TX fuel, the second to the LA fuel.

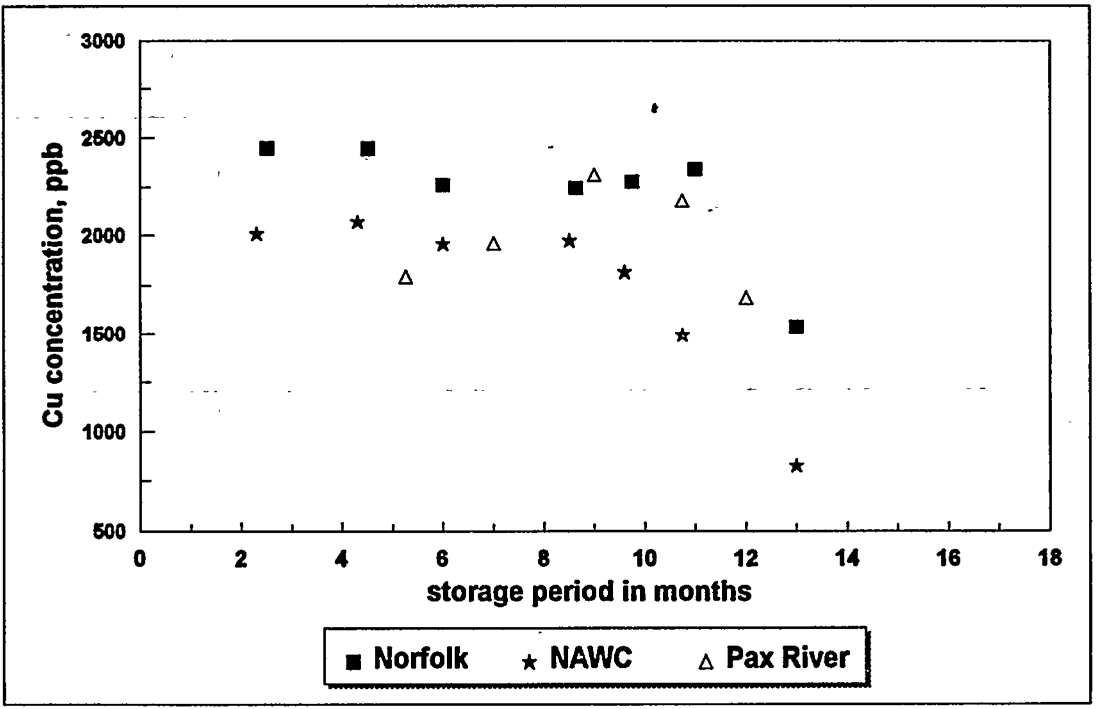

Figure 1. For fuel set A: fuel solubilization of copper from Cu-Ni plates on ambient storage for 0-13 months.

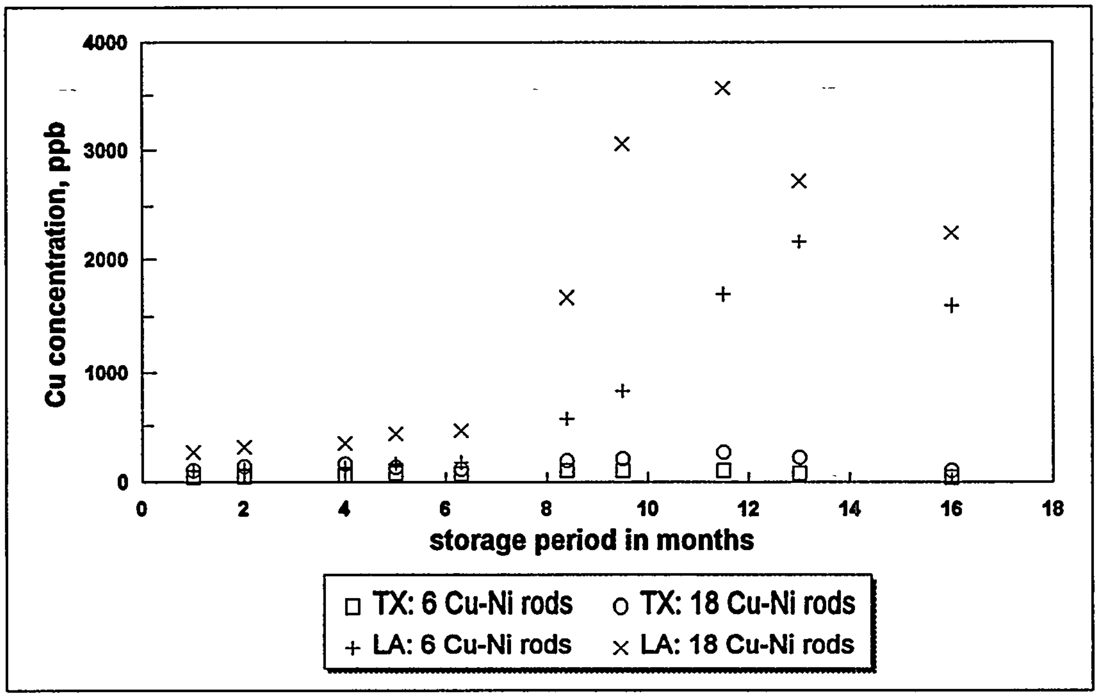

Figure 2. For fuel set B: fuel solubilization of copper from Cu-Ni rods on ambient storage for 0-16 months.

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INVESTIGATION OF THE EFFECTS OF TIME ON THE PHYSICAL COLLECTION OF AVIATION FUEL DEPOSITS IN A SCALED TURBULENT FLOW SYSTEM

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[2]194 Teal Circle, Berlin, MD 21811, USA.

ABSTRACT

The Fuels & Lubricants Division of the Naval Air Warfare Center has developed and verified a hypothesis which models the collection and buildup of aviation fuel carbon deposits as a function of time in a turbulent flow simulator (i.e., fuel injector nozzle). These deposits are the result of thermal oxidative breakdown that typically occurs when aviation fuels are exposed to the different heat loads rejected into various parts of an aircraft fuel system (viz., fuel injector nozzles) during flight operations. This paper presents experimental data that supports the use of a proposed mathematical model used in describing the fuel thermal deposition process and provides theory upon which the model is based. Assumptions are made which enable this model to be used in calculating the deposition rate within a turbulent simulator over a wide range of typical temperature conditions of an aircraft fuel system. The intended use of this work is to develop a test protocol that will require less test time and fuel in order to study the effects of fuel thermal stability using a high fuel flow unit.

I. PURPOSE

The purpose of this research program is to propose and validate a hypothesis (via experimental data) which models the collection and buildup of aviation fuel deposits as a function of time in a turbulent flow simulator (i.e., fuel injector nozzle)[1].

In addition, it will be demonstrated how this hypothesis is fitted to the Arrhenius expression with a constant slope that is representative of all fuels operating at temperature conditions typically encountered in actual Naval aircraft fuel systems. It will be further demonstrated how this modified Arrhenius expression is used as the basis for the Navy's improved test protocol. This protocol will be used to estimate, on a relative basis, the coking tendencies of generic aircraft fuel injectors and will eventually assist in defining the coking behavior of various fuels operating under an actual aircraft temperature environment. The turbulent flow system used to conduct these experiments is the Naval Aviation Fuel Thermal Stability Simulator (NAFTSS) which is owned operated by the Fuels & Lubricants Division of the Naval Air Warfare Center (NAWC) currently located in Trenton, NJ. A flow schematic showing the major test sections of the NAFTSS is shown in Appendix 1 (p. A-1).

II. OBJECTIVES

1. Conduct time-controlled experiments to validate the preliminary theory addressing the deposition collection process that occurs in the fuel injector nozzle of the NAFTSS unit. To establish this hypothesis, experiments should include test conditions typically encountered in actual aircraft fuel systems.

2. Calculate a deposition constant at constant temperature and determine NAFTSS unit life expectancy from the experimental data using the following equation:

$$\mathbf{W = C * t^3} \qquad 1)$$

where,

W = Weight of the carbon deposit in the NAFTSS nozzle tube **(mg)**
t = NAFTSS test duration **(hours)**
C = Collection Constant which represents fuel quality with respect to the deposition collection behavior in the NAFTSS nozzle tube at a specific nozzle wetted-wall temperature between 350-600°F **(mg/hr^3)**

3. Incorporate the collection constant into the classical Arrhenius expression[2, 3] to achieve an expression with a slope that is assumed to be constant for all fuels. Select a representative fuel/operating condition and conduct experiments to calculate a range of collection constants for wetted-wall temperatures between 450 and 600°F. Use this data to calculate a constant slope for the modified Arrhenius expression.

III. THEORY ON SURFACE DEPOSITION

The deposition collection process that occurs inside a clean, unused (i.e., deposit-free) fuel injector nozzle under heat loads experienced during aircraft flight operations can be viewed as three (3) distinct time periods, described in detail in the sections that follow.

A. Deposition Collection Process for a Generic Fuel Injector

(1) *Pre-Induction Period*

As defined by the Shell-Thorton studies[4], the pre-induction period occurs when the virgin metal surface of a clean fuel injector becomes initially coated with deposits. This is evidenced by a low rate of surface deposition when the tiny deposit particles are released from the fuel. These particles are trapped within the microscopic crevices located on the inside surface of the fuel injector nozzle. These surface irregularities are the result of the injector's manufacturing process.

(2) ***Induction Period***

During this period the inside metal surface of the same fuel nozzle is covered with a mono-layer of deposits. This results in increased surface roughness which promotes better collection of subsequent deposits. This period represents a major transition in the deposition collection process.

(3) ***Post-Induction Period***

This post-transitional period is evidenced by a high rate of surface deposition which appears to be constant when extrapolated to some point in time. At this point the particle adhesion continues at a high rate until some theoretical failure point is reached. We arrive at this point when a reduction in the nozzle diameter affects the fuel flow path of the nozzle.

B. **Deposition Collection Process for the NAFTSS Nozzle Tube**

The test conditions in the NAFTSS are run at steady state conditions of constant wetted-wall temperature, heat transfer, and fuel flow rate. The chemical kinetic rate of deposit formation from the fuel can also be assumed constant.

At the beginning of a test when the nozzle tube is deposit-free, the amount of particles that adhere to the surface is only a small percentage of the total deposit particles released from the fuel and the collection sites are random. The remaining particles pass through the nozzle and into the NAFTSS Hot Filter Section, which contains a sintered steel filter with a nominal porosity of 60 μ. As the test progresses, the microscopic crevices that exist in the nozzle become randomly filled and a mono-layer of deposit begins to form. From this point on, a major transition period occurs whereby more and more particles adhere to the nozzle wall and fewer particles pass through the exit of the nozzle. This is referred to as the Induction Period and the deposit adhesion to the mono-layer increases dramatically.

Following this major transition period, the tube collection efficiency is at its maximum which initiates the Post-Induction Period. At this time the surface deposition rate inside the nozzle is very high and constant. This causes a major portion of the deposits to cling to the inside of the metal surface until the nozzle tube approaches some theoretical failure point. Before the tube reaches this point, a significant rise in the (measured) wetted-wall temperatures of the NAFTSS nozzle tube will be observed due to the insulating properties of the accumulated deposit particles. This large disturbance indicates the test should be terminated. Based upon the theory of deposit growth, it was perceived that a non-linear power equation would be best suited to model these events. It was not until actual data was collected and analyzed that the cubic equation (from equation 1) above was selected to best approximate the deposition process.

IV. ANALYSIS OF TEST DATA

(1) *Verification of Hypothesis ($W = C * t^3$)*

Contained in the table in Appendix 2 (p. A-2) is the entire test program designed to study the use of the collection model. Some of these experiments under the listed conditions are still in the process of being studied. The first three conditions, however, have been completed and are presented as follows:

(a) neat fuel at baseline conditions
(b) neat fuel at higher/lower wetted-wall temperature
(c) neat fuel with dissolved copper at baseline conditions

For NAWC JP-5 (Neat), a total of seven (7) tests were performed at baseline conditions. The data showed an excellent correlation using the equation $W = C * t^3$. The value of r^2 (coefficient of determination) is 0.935 and is shown in the graph in Appendix 3 (p. A-3). This can be interpreted as 93.5% of the variation in deposit (carbon) weight (W) is caused by the underlying variation in test duration (t). The value of the Collection Constant, C, obtained from the equation can be used further to calculate deposit growth over any period of time for a wetted-wall temperature of 550°F.

The other two (2) conditions, i.e., NAWC JP-5 at higher/lower wetted-wall temperature and NAWC JP-5 + 250 ppb Copper, also demonstrate an excellent correlation to the model as shown by the graphs in Appendices 4 and 5 (pp. A-4 and A-5), with r^2 values of 0.915 and 0.904, respectively. Their respective C values are also shown in these graphs. For all other test conditions run, r^2 values and Collection Constant (C) data, as well as other pertinent data, are listed in the table in Appendix 6 (p. A-6).

(2) *Arrhenius Expression (Ln C = Ln A - 16610/T)*

As shown in Appendix 7 (p. A-7), Collection Constant (C) values generated from NAWC JP-5 (Neat) are shown for wetted-wall temperatures at 450, 500, 550, & 600°F. This data was used to modify the Arrhenius expression for predicting deposition collection behavior at lower (extrapolated) wetted-wall temperature conditions. As shown in the this graph, this data fits the Arrhenius expression quite well, with an r^2 value of 0.9274, a y-intercept value for Ln A of 21.616, and a slope (E_a/R) of -16,610. This means that 92.74% of the variation in "the natural logarithm of the Collection Constant" (Ln C) can be explained by the variation in the reciprocal temperature, 1/T (in °K). Since these test conditions represent the baseline conditions and have the most Collection Constant (C) data with respect to wetted-wall temperature, the slope value of -16,610 will be an assumed constant representing the "Average Apparent Energy" of activation for all fuels/operating conditions. As more data becomes available, a new average will be used to adjust the slope.

For NAWC JP-5 + 250 ppb Copper, the Arrhenius expressions for this data is shown in Appendix 8 (p. A-8) for wetted-wall temperatures from 450 through 600°F, inclusive. As shown by the Least Squares equation for this data, an r^2 value of 0.8048 was established, thus indicating a strong correlation between C and 1/T. Since we have previously assumed that the same thermal oxidative breakdown mechanism will exist for all fuels/operating conditions (i.e., a constant slope condition for the Arrhenius expression), this data can be adjusted to fit the slope of -16610. After this is accomplished the value of the y-intercept (Ln A) will also be adjusted accordingly as shown in Appendix 8 (p. A-8). After adjusting the slope, a fairly good correlation exists, thus verifying the validity of the hypothesis and the corresponding assumptions, viz., that of the kinetic rate of deposition remains the same for all fuels/conditions.

A summary of all pertinent parameters relating to the deposition collection model and the Arrhenius expression is shown in the table in Appendix 6 (p. A-6) for all the tests performed in this study to date. Once the hypothesis has been proven for all fuels/operating conditions, all other tests run at wetted-wall temperature between 450-600°F (inclusive) can be fitted to the modified Arrhenius expression with constant slope of -16610. Furthermore, the relative coking tendencies of any fuel/operating condition can determined by calculating the adjusted value of "A" for the condition of interest and dividing it by the value of "A" for NAWC JP-5 (neat) at baseline conditions. By definition the relative ranking of the baseline conditions would be "1".

V. CONCLUSIONS

1. The deposition collection model, $W = C * t^3$, has been validated for representative fuels and operating conditions typically encountered in actual Naval aircraft fuel systems. These conditions include fuel quality, fuel injector wetted-wall temperature, bulk fuel temperature, copper contamination, and thermal stability improving additives.

2. The deposition collection model, $W = C * t^3$, has been successfully fitted to the modified Arrhenius expression to predict coking tendencies of various fuels/operating conditions in the NAFTSS for wetted-wall temperatures from 350-600°F.

3. The NAFTSS test protocol, using the deposition collection model as its foundation, can evaluate the relative coking tendencies of any fuel/operating condition experienced in an actual

aircraft fuel system by performing one test to the post-induction period of the nozzle tube (see Appendix 9, p. A-9). This is equivalent to a nozzle carbon deposit of approximately 10-12 mg.

4. Collection Constant data from the NAFTSS, in conjunction with the modified Arrhenius expression ($\mathrm{Ln}\ C = \mathrm{Ln}\ A - 16610/T$), can be used to help better define and assess the impact of coking (i.e., thermal oxidative breakdown) that typically occurs at temperatures in actual fuel injectors. This can be accomplished by calculating the relative ranking of a given fuel/operating conditions from NAFTSS data by taking the value of "A" at the specific condition of interest and dividing it by the value of "A" for the baseline conditions.

5. Alternatively, relative coking tendencies of various fuels/operating conditions can be assessed with respect to "time to failure" of the NAFTSS nozzzle tube. This can be accomplished by calculating the failure time (t_f) in the NAFTSS for the specific condition of interest and dividing by the failure time for the baseline conditions. Assuming that a carbon deposit of 20 mg constitutes a failure in the NAFTSS nozzle tube, failure time at a specific wetted-wall temperature can be calculated as follows:

$$t_f = (W / C)^{1/3} \qquad 2)$$

6. The NAFTSS test protocol appears to be the best and most cost effective means of ranking the coking tendencies of various fuels/operating conditions.

REFERENCES:

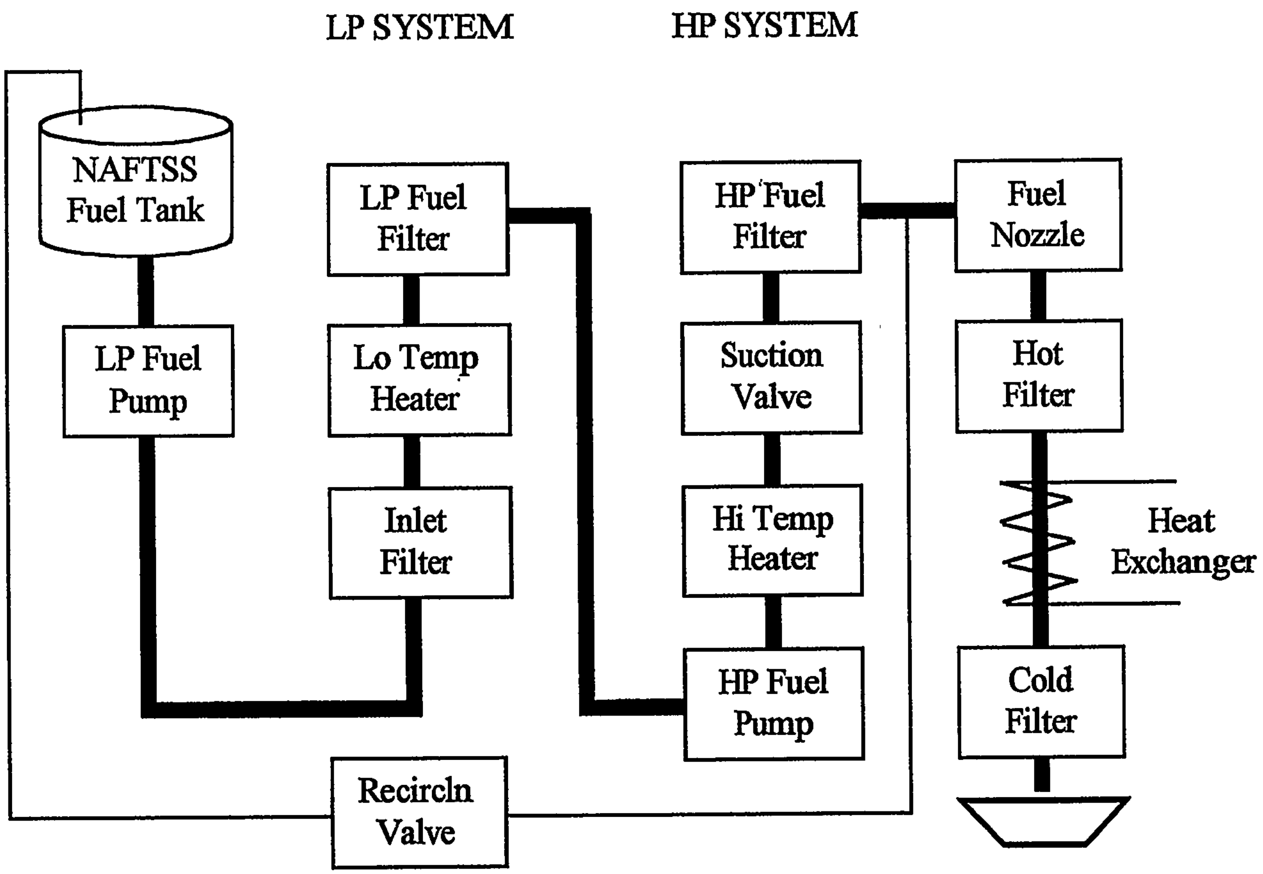
(1) "Investigation of Surface Collection Efficiency on System Performance," Proposal submitted by C.J. Nowack under AERA Contract No. N68335-94-D-0024, March 26, 1996.

(2) Por, Nahum, "Stability Properties of Petroleum Products," The Israel Institute of Petroleum and Energy, The School of Petroleum and Energy Sciences, March 1992.

(3) Hazlett, Robert N., "Thermal Oxidation Stability of Aviation Turbine Fuels," ASTM Publication Code Number (PCN) 31-001092-12, 1991.

(4) Clark, R.H. and Wolveridge, P.E., "Induction Periods: Are You Measuring the Right Rate?", Presented at CRC-Aviation Fuel Meeting, CRC Project No. CA-43-67, April 1993.

APPENDIX 1: NAFTSS FLOW SCHEMATIC



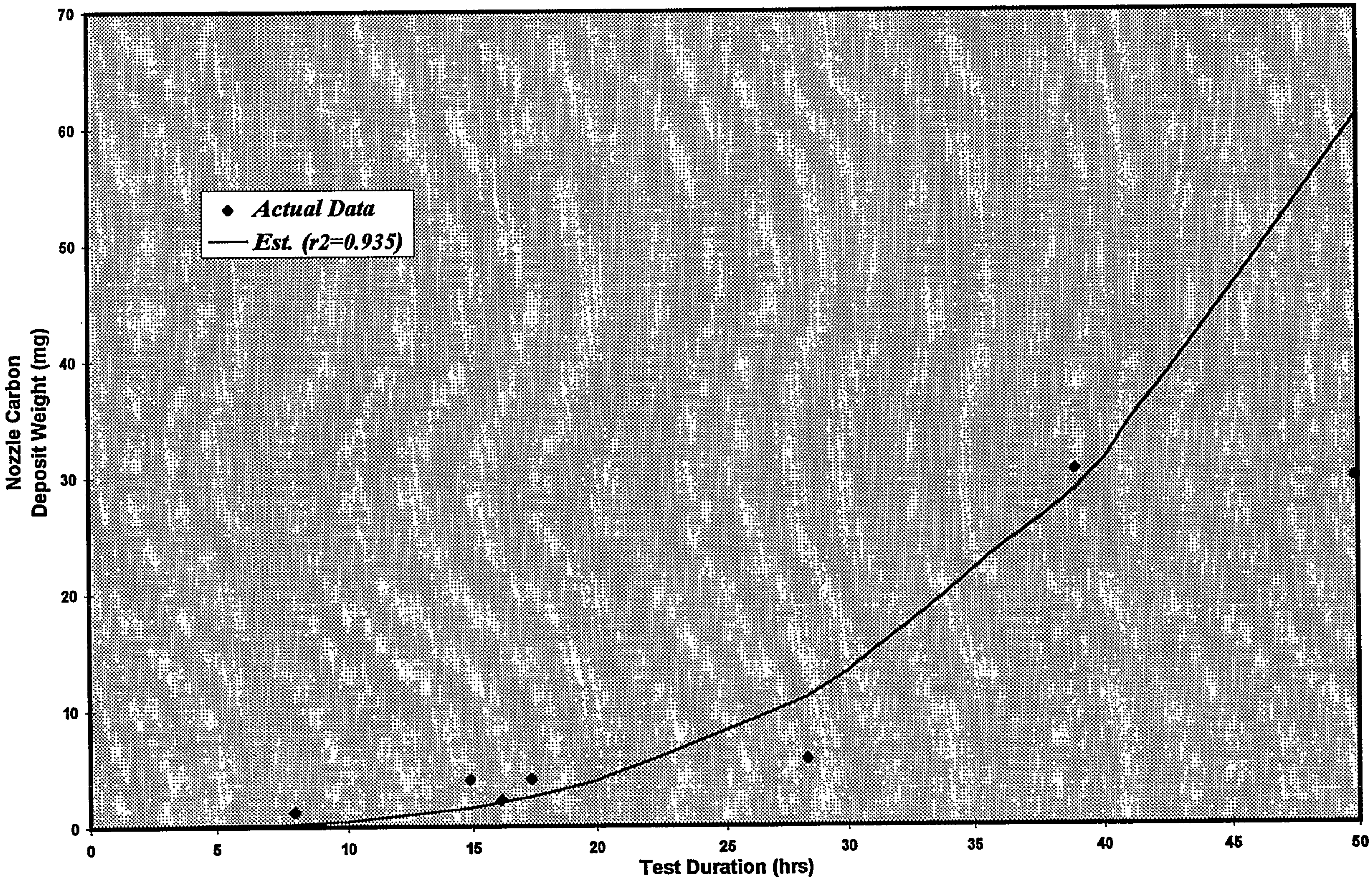
APPENDIX 2: NAFTSS TEST PLAN TO VALIDATE HYPOTHESIS

TEST CONDITION	FUEL TYPE	ADDITIVE TYPE	ADDITIVE CONCENTRATION (ppm)			JFTPT BPT	LP FILTER / AIRFRAME TEMP			HP FILTER / FMU TEMPERATURE			WETTED-WALL TEMP				NO. OF TESTS[1]
			Low	Effec.	High	°F	100°F	150°F	200°F	300°F	320°F	340°F	450°F	500°F	550°F	600°F	
Baseline Conditions	NAWC JP-5 (Neat)	N/A	N/A	N/A	N/A	520	X			X					X		7
Higher/Lower Wetted-Wall Temperature	"	"	"	"	"	"	X			X						X	3
Higher/Lower HP Filter Temperature	"	"	"	"	"	"	X				X				X		3
"	"	"	"	"	"	"	X					X			X		3
Copper Contamination	NAWC JP-5 + 250 ppb Cu	"	"	"	"	< 400	X			X					X		3
Thermal Stability Improving Additives	NAWC JP-5 (Neat)	MDA		5.8 (w/v)		> 575	X			X					X		3
"	"	Betz 8Q462		256 (v/v)		"	X			X					X		3
Hot Fuel Recirculation (future)	NAWC JP-5 (Neat)	N/A	N/A	N/A	N/A	520	X			X					X		3

NOTES:

(1) At least one (1) test should be run in each of the three (3) induction modes, i.e., Pre-, Regular, & Post-Induction periods

APPENDIX 3: BASELINE CONDITIONS
NAWC JP-5 (Neat)
LP Filter=100°F, HP Filter=300°F, Wall B=550°F
$W = 4.8777E\text{-}04 * t^3$

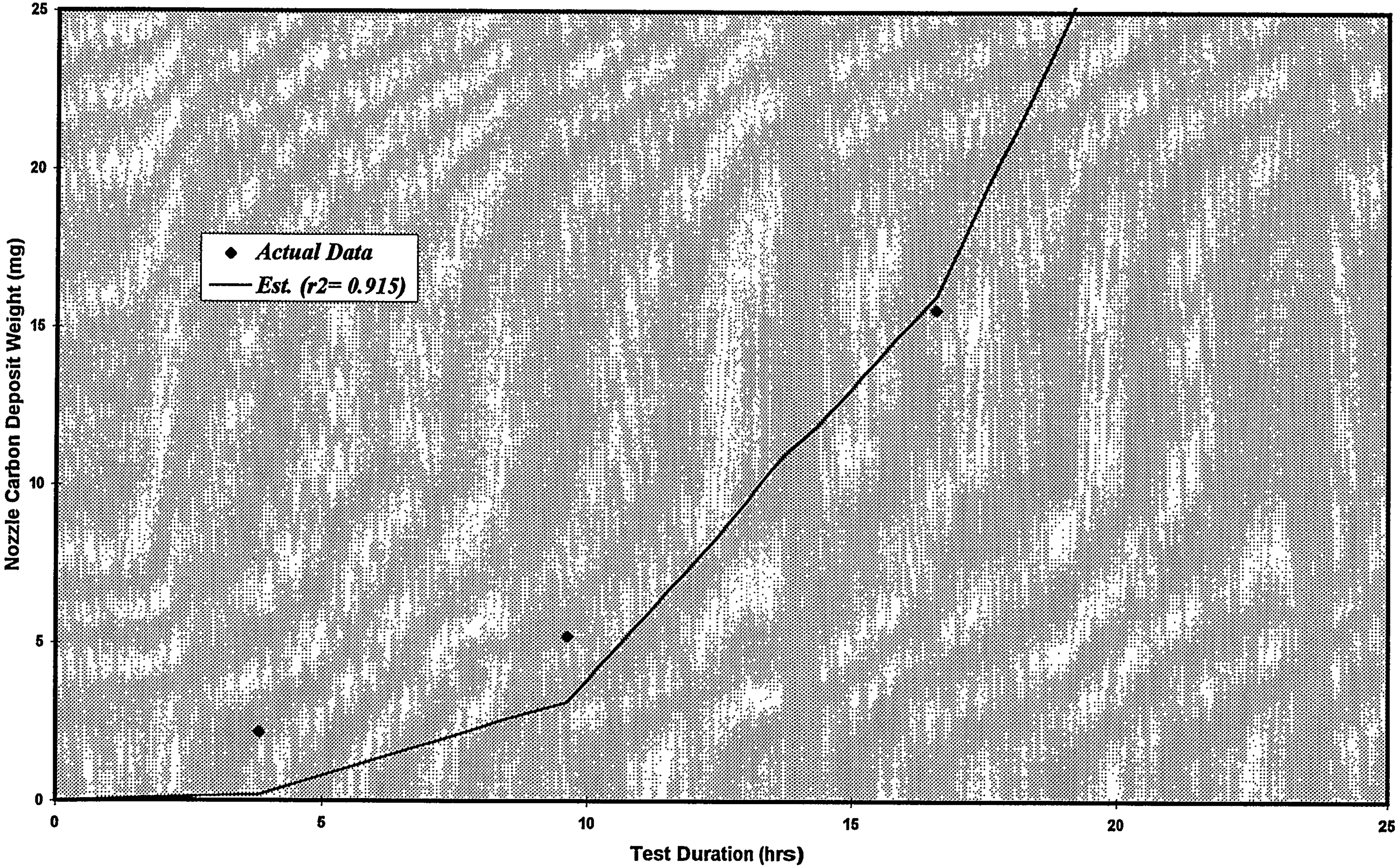


APPENDIX 4: EFFECT OF HIGHER/LOWER WALL TEMPERATURE

NAWC JP-5

LP Filter=100°F, HP Filter=300°F, Wall B=600°F

$W = 3.5184E\text{-}03 * t^3$

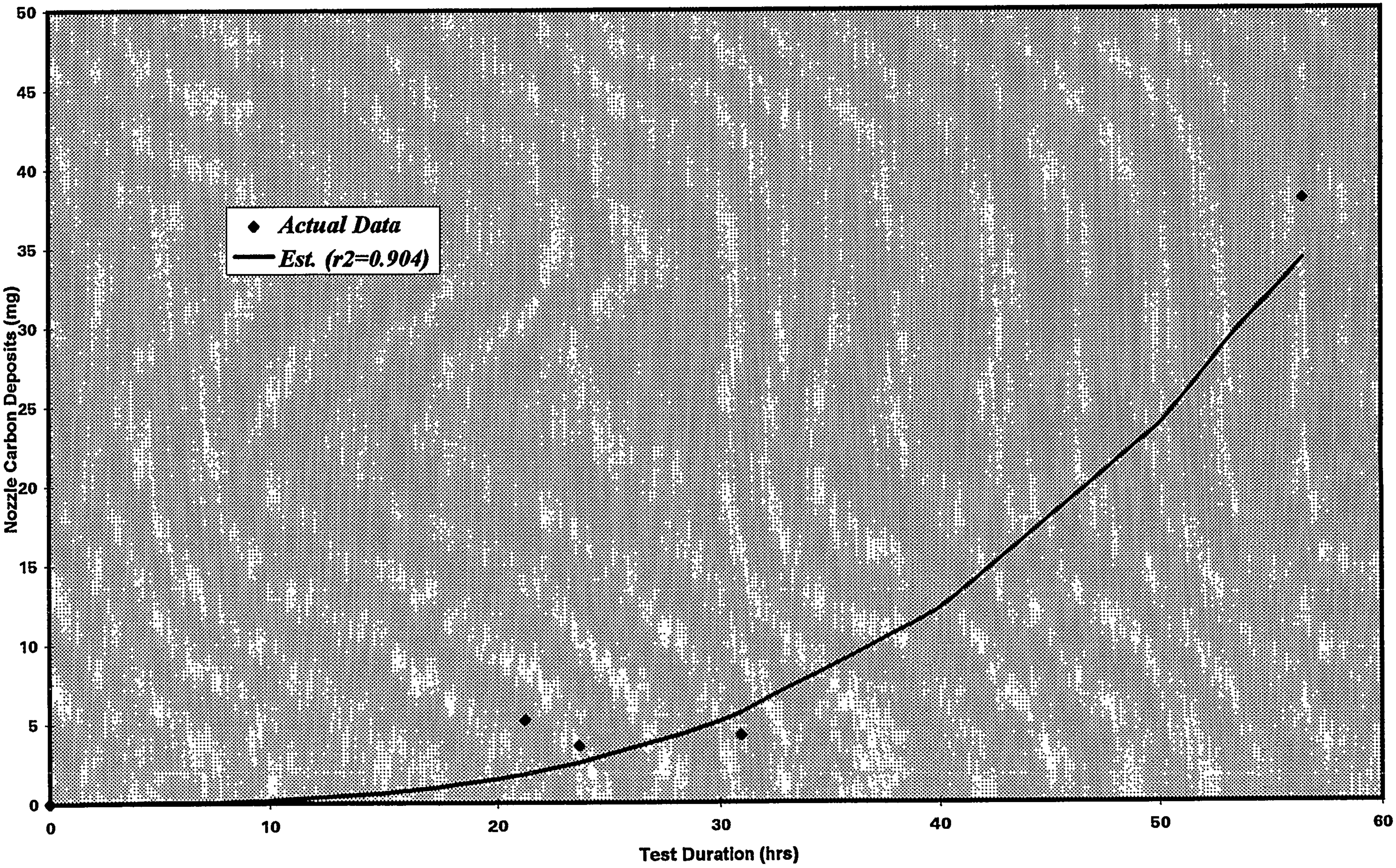


APPENDIX 5: EFFECT OF COPPER

NAWC JP-5 + 250 PPB COPPER

LP Filter=100°F, HP Filter=300°F, Wall B=550°F

$W = 1.90E\text{-}04 * t^3$



APPENDIX 6
NAFTSS TEST DATA TO VALIDATE HYPOTHESIS

$$W = C * t^3; \; C = A * \exp(-16610/T)$$

$$\text{Ln } C = \text{Ln } A - 16610/RT$$

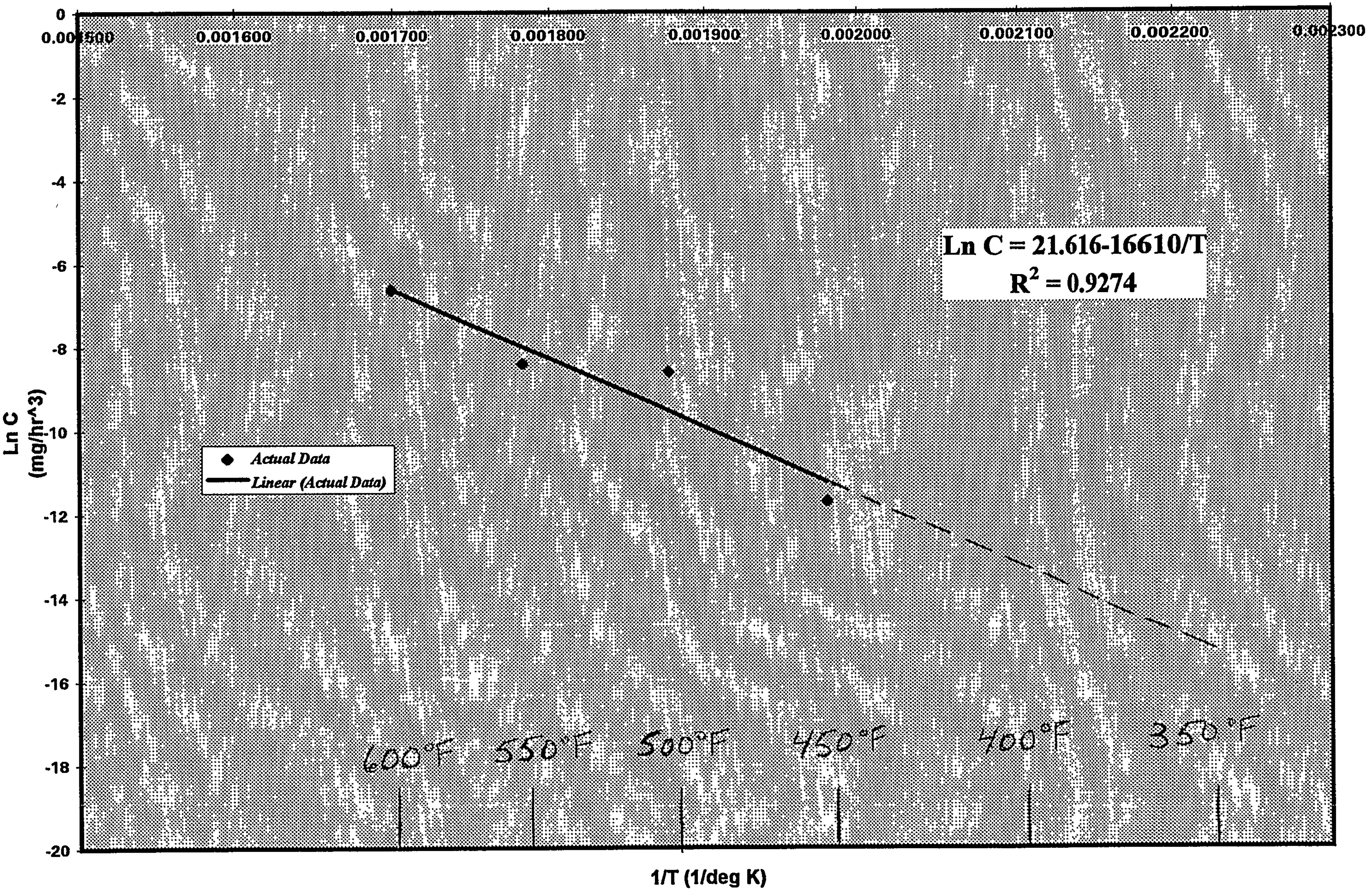
TEST CONDITION	FUEL TYPE	JFTOT BPT	LP FILTER / AIRFRAME TEMP			HP FILTER / FMU TEMPERATURE			WETTED-WALL TEMP				$W = C * t^3$		ADJUSTED Ln A	RELATIVE RANKING (of A)
													C	r^2		
		°F	100°F	150°F	200°F	300°F	320°F	340°F	450°F	500°F	550°F	600°F	mg/hr^3	(unitless)	mg/hr^3	(unitless)
Baseline Conditions	NAWC JP-5 (Neat)	520	X			X					X		4.8780E-04	0.935	21.616	1.00
Higher/Lower Wetted-Wall Temperature	"	"	X			X						X	3.5184E-03	0.915	22.572	2.60
Higher/Lower HP Filter Temperature	"	"	X				X				X		8.2440E-04	0.784	22.519	2.47
"	"	"	X					X			X		1.8654E-03	0.91	23.335	5.58
Copper Contamination	NAWC JP-5 + 250 ppb Cu	< 400	X			X					X		1.9000E-04	0.904	21.051	0.57
Thermal Stability Improving Additives	NAWC JP-5 + 5.8 mg/L MDA	> 575	X			X					X		5.4946E-05	0.984	19.810	0.16
"	NAWC JP-5 + 256 ppm (v/v) Betz 8Q462	> 575	X			X					X		N	N	N	N
Hot Fuel Recirculation (future)	NAWC JP-5 (Neat)	520	X			X					X		N	N	N	N

(1) "N" denotes that test has not been run yet.

APPENDIX 7: BASELINE CONDITIONS

NAWC JP-5 (Neat)

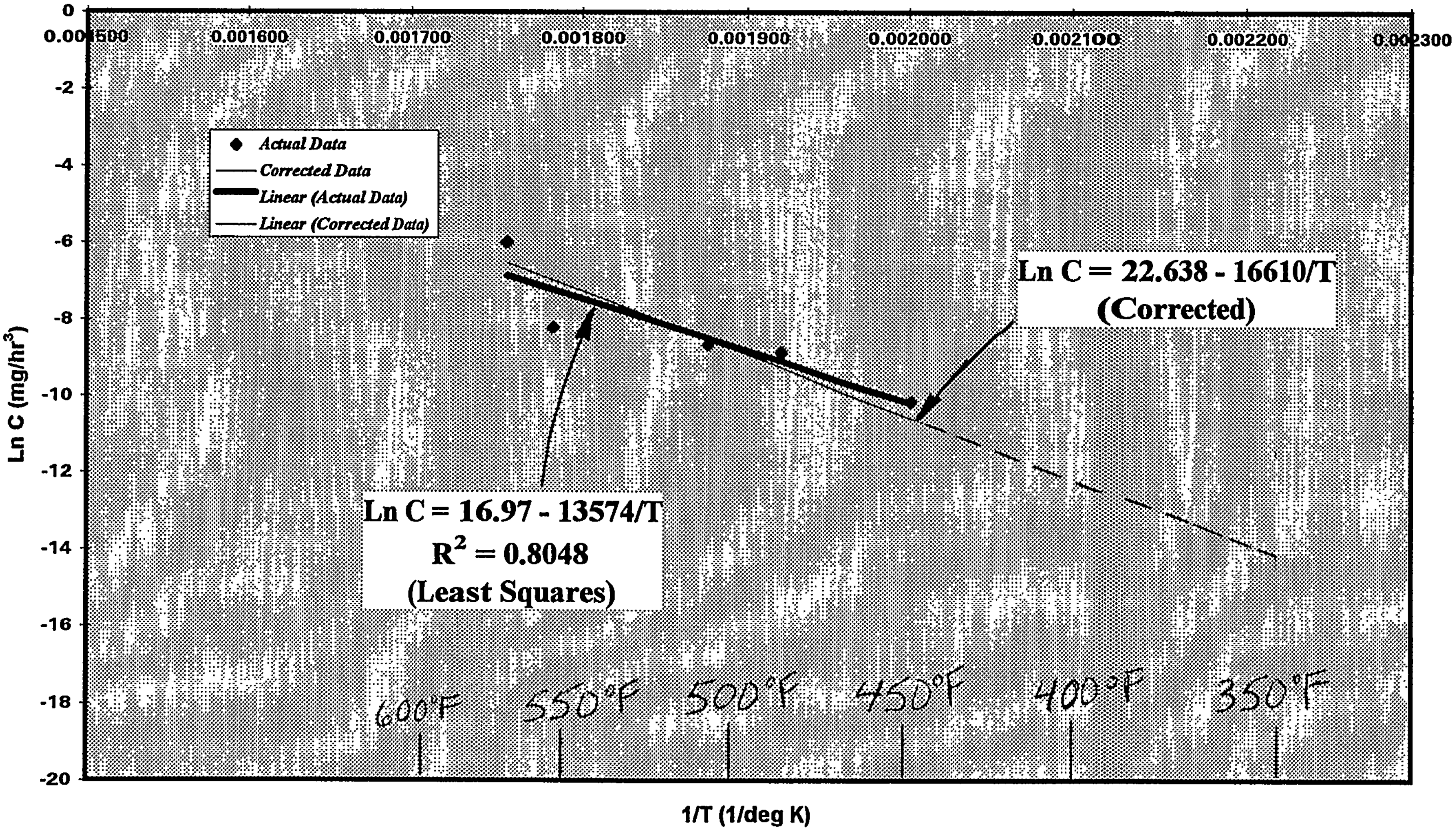
LP Filter=100 F, HP Filter=300 F, Wall B=350-600 F`



APPENDIX 8: EFFECT OF COPPER

NAWC JP-5 + 250 PPB COPPER

LP Filter=100°F, HP Filter=300°F, Wall B=350-600°F



APPENDIX 9: NAFTSS TEST PROTOCOL FOR EVALUATING FUELS/OPERATING CONDITIONS

1. Run tests under desired operating conditions (i.e., fuel type, bulk fuel temp, neat vs. additized, copper, hot fuel recirculation, etc.) at a NAFTSS nozzle wetted-wall temperature of 550°F.

2. Continue running test until the nozzle tube wetted-wall temperature (wall B) rises to the point that indicates that the beginning of the Post-Induction period has been reached. This is equivalent to a nozzle tube deposit of approximately 10-12 mg.

3. At the end of the test, perform surface carbon analysis on the nozzle tube using the LECO Carbon Analyzer. Calculate the Collection Constant, C, based on knowledge of the carbon deposit weight (W) in the nozzle tube and the test duration (t). This can be calculated by manipulating equation 1 to the following form:

$$\mathbf{C = (W / t^3)} \qquad 3)$$

4. Using the calculated value of C from step 3 above and the initial wetted-wall temperature (wall B), find the value of A in the modified Arrhenius expression shown below:

$$\mathbf{Ln\ C = Ln\ A - 16610/T} \qquad 4)$$

Knowing the value of A will give you the value of C over the range of wetted-wall temperatures from 350-600°F for any fuel/operating condition.

5. Once the C value is determined for a specific fuel/operating condition, predictions can be made with respect to the expected life (in hours) of the NAFTSS nozzle tube. Predicted life expectancy can be determined using the assumption that 20 mg carbon is equivalent to a failure in the

NAFTSS nozzle tube. Thus, time to failure can be calculated by re-arranging equation 1 to the form of equation 2 as previously shown:

$$t_f = (W / C)^{1/3} \qquad 2)$$

5. Alternatively, fuels can be ranked by taking the ratio of the C value at the specific conditions of interest and comparing to some known baseline value.

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EVALUATION OF JP-8 + 100 FUEL COMPATIBILITY WITH AIRCRAFT FUEL SYSTEM MATERIALS: THE EFFECT OF DETERGENT/DISPERSANT ON AIRCRAFT MATERIALS

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Abstract. Within airframe and engine fuel systems, materials including metallics, composites and non-metallics are found in contact with aircraft fuel. This paper describes a few of these materials and physical property changes observed in these materials after thermal aging in specific aircraft fuels in a laboratory setting. These changes are evaluated in comparison to physical properties of materials before fuel aging and with different test fuels and additives. The laboratory tests are designed to reasonably replicate temperatures to which the materials and the specific fuels would be subjected in airframes and engines. The 28 day aging test temperatures range from ambient to 400 ° F. The materials are identified according to use categories in aircraft fuel systems. The materials include those used in fuel system tanks and in associated components (bladders, sealants, locking devices) as well as alloys and sealing materials used in fuel lines and components up to the engine combustion chamber. Included in the test data points are the materials' effects on the fuel i.e. conductivity, elements, gums, acid number and hydroperoxides. This paper describes aircraft fuel system materials and their compatibility with a new higher thermal stability fuel. The improved thermal stability JP-8 fuel is obtained by incorporating a fuel additive package commonly referred to as JP-8 +100. The effects of this fuel additive on the aircraft fuel systems materials are measured and determined by comparing their effects to that of a baseline JP-8 fuel. The +100 refers to the increase in the expected thermal stability range of the fuel by 100 ° F over that of a JP-8 baseline fuel. The +100 fuel additive package incorporates dispersant / detergent, metal deactivators and antioxidant compounds which are incorporated to reduce the rate of oxidation and deterioration of fuel at higher temperatures.

Introduction. The stated objective of this evaluation is to: "Demonstrate by comparative thermal aging tests and analysis that JP-8 fuel, containing a thermal stability additive package (detergent and dispersant) does not deteriorate or oxidize the contacted fuel system materials to the extent that degraded system performance ultimately occurs; i.e., fuel leakage and/or component malfunction".

The scope of this paper includes not only an examination of the compatibility effects of the thermal stability fuel additive in normal and 4x (times) concentrations on certain fuel system materials, but also illustrations of the critical importance of the time/temperature selection criteria for fuel system materials which experience the temperature variances in the air vehicle environment. The Department of Defense inventory includes an extensive number of both older and newer aircraft types and models. More than two hundred thirty-five materials which come in contact with fuel have been identified for the subject evaluation. Consequently, this paper can, as a practical matter, discuss only the results of a few material examples.

The material tests were designed to examine and document two fuel / fuel system materials compatibility issues. The first issue was whether the *physical properties* of the fuel system materials examined in this test were affected by the JP-8 fuel *with* the +100 TSA (thermal stability additive) *to any greater degree* than they were affected by JP-8 fuel *which did not contain* the additive. The second issue was identification of those fuel system materials physical properties which were affected by the time / temperature in JP-8 fuel in *any* or *all* of the tests. Materials which *"failed" any physical property test in JP-8 and / or JP-8 + 100* were considered for an evaluation in an aircraft component / system fuel flow dynamic test stand specifically designed for these tests.

The tests examined a wide range of physical properties. Identical material samples were immersed in JP-8 fuel and in JP-8 +100 fuel and subjected to aging at appropriate temperatures (see "Aging Temperatures"). Data for each material's physical properties was collected and recorded in laboratory data collection sheets. This data was compiled on individual test data sheets (where all test data for *one* material were recorded on *one* sheet). Thus, comparisons between pre- and post- test material physical properties could be made as well as comparisons between JP-8's and JP-8 + 100's impacts on the materials physical properties. In addition, the test data was compiled into test summary sheets (where *comparisons* between the effects of the JP-8 and the JP-8 +100 in the various test temperatures could be easily discerned).

The current methods for evaluating materials which come in contact with fuel are separated into two basic categories: those methods used for evaluating metallics and those used for evaluating non-metallics. The methods used to evaluate materials' physical properties in a free state (non-component system application) may not necessarily reveal the materials' performance in an actual aircraft application. For example, physical property loss, and/or corrosion which may ultimately result in fuel leakage and/or component malfunction may not be determined in this laboratory test series. The correlation of the materials' free state aging to an actual aircraft component / system fuel flow dynamic application is a part of the overall planned program evaluation. One such material, "leaded bronze", was tested in an engine gear pump, the test and results are discussed in this paper. Additional testing of "O" ring seals is planned to correlate component application test results to the static tests results.

In the following discussions, two non- metallics and one metallic will be examined in some detail. The tests on the two non-metallics will examine the materials' thermal tolerance. The tests on a leaded bronze alloy material will show the effects of the fuel with and without the + 100 fuel additive. Fuel / temperature aging effects on the material are demonstrated by the data when compared to non-aged material. Improved properties resulting from the effects of the additive also will be demonstrated.

Test Materials Identity. An early vigorous investigative effort of both industry and governmental agencies resulted in a comprehensive list of the materials used in airframe and engine fuel systems.

Aging Temperatures. Test temperatures were determined as practical laboratory approximations of use conditions. Four primary test temperatures were selected for this fuel/material evaluation. The primary test temperatures chosen were: 160 ° F; 200 ° F; 325 ° F; and 400 ° F. The temperatures were determined as follows:

For existing airframe fuel systems, 160 ° F generally is an accepted "high" temperature range. However, new and future airframe systems which have fuel recirculation from the engine back to the airframe fuel tanks may require continued operation up to 200 ° F. This test temperature exposure would provide a list of materials which could safely operate in fuel systems at 200 ° F and those which could not be used. A 325 ° F fuel temperature exposure was chosen for most materials commonly found on the aircraft engine. A 400 ° F fuel temperature exposure was chosen for the higher temperature sections of the aircraft engine.

In a limited number of instances, test data indicated the usefulness of other temperature exposures as dictated by a particular aircraft application. These are noted where they were used.

Fuel and Fuel Additives. The baseline fuel used in the subject tests was Jet A with the additives (static dissipater, icing and corrosion inhibitors) which, when added to Jet-A, produce fuel appropriately designated as JP-8. The two test fuels were produced by adding Betz Dearborn additive (at 100 mg/l and 400 mg/l concentrations). The BETZ additive package 8Q462 has dispersant and detergent properties. In addition a metal deactivator (MDA) at 2 mg/l concentration and antioxidant (BHT) additive at 25 mg/l concentration are part of the Betz additive package. The MDA and BHT already were qualified additives. The BHT was not added in a 4x concentration. However, the MDA, for this test evaluation, was in a 10 mg/l concentration, higher than current specifications which require a 2 mg/l concentration.

Test Duration. The test duration for each material was twenty-eight days with a fuel changeout cycle of seven days.

Materials Categories. Following is a list of categories of materials examined in the subject test series grouped according to their use in aircraft airframe and engine fuel systems and in ground tank and fuel storage systems. (Each category may include many different materials and types of materials from a variety of manufacturers.)

Adhesives; Fuel Bladder Materials; Coatings; Primers; Sealants; Composites (used in fuel tanks, vent lines and isolator tubes, etc.); Fuel Filter Materials; Explosion Suppression Materials (foams); "O"-Ring Materials; Gasket and Washer Materials; Hose Materials; Insulation /Electrical/Wire/Clamps/Misc; Joining Materials; Bearing Materials; Locking Device Materials; Airframe, Tank and Plumbing Materials; Engine, Fuel Line and Components Materials; Float Materials; Potting Compound Materials.

Material Properties Test Evaluation. The data pages selected for these materials represent non-metallics tests with two different "O"-ring elastomeric materials and illustrate material property changes i.e.: tensile, elongation, volume swell, hardness (shore) and compression set. The tests with these non-metallics also show changes in the fuels properties which include color, fuel acid number, gums, hydroperoxides and fuel conductivity.

The metallic tests show material property changes i.e.: weight, color, and pitting (visual and microscopic). The tests with the metallic materials also evaluate fuel property changes including color, fuel conductivity and fuel materials elemental changes by use of graphite furnace and/or inductive coupled plasma test equipment.

The evaluation of physical properties related to other categories of fuel system materials tested includes pencil hardness, lap shear, cohesion, tape adhesion, peel strength, laminar shear, resistivity and torque.

The data pages compare the materials' properties aged in a JP-8 baseline fuel and with the JP-8 fuel containing a thermal stability additive in a normal concentration and in X 4 concentration.

In order to facilitate the evaluation of the non-metallic materials property changes, control material tests at ambient temperatures (72 ° F) also are performed and recorded.

Allowable tolerance ranges for the material property changes were established based on each material's specification requirements tempered with the constraints and conditions of each test. These tolerance ranges provide the test evaluation criteria for judging the performance of the materials fuel temperature aging test results.

Discussion. Following is a brief discussion of some of the findings of the subject tests.

Nitrile (MIL-P-5315) "O"-Rings. Fuel seals are of vital importance to proper function and fuel containment of a fuel system and the components thereof. Seals/ gaskets normally are in the form of "O"-rings and are found throughout the fuel system both within the confines of the fuel tanks, and, perhaps most importantly, outside the fuel tanks. Outside the tanks, they are found extensively in fuel couplings, valves, pumps, fuel tank interconnects and in ground and aerial refueling lines and components. These "O" rings prevent fuel leakage, a paramount safety concern because of the fuel's inherent volatility. In addition "O"-ring failure can affect the proper functioning of fuel system components and sub-systems.

This material's (Nitrile, MIL-P-5315, "O"-Rings) post physical properties after a 28 day aging in JP-8 and with the + 100 and + 100 X 4 thermal stability additives generally performed fully satisfactorily at a temperature of 160 ° F as illustrated in Table #1. However, its physical properties were degraded to an unacceptable level at temperatures of 180 ° F with JP-8 and +100 additive as illustrated in Table #2. At temperatures of 200 ° F and 325 ° F, the material exhibited extreme degradation of its physical properties to the extent that they could not be measured (Tables #3 and #4). For some properties, in Table #1 it can also be noted that a significant improvement in the nitrile physical properties occurs with fuel containing the thermal stability additive over the baseline JP-8 fuel to the extent that they approach the control material which has had no temperature/fuel aging. This positive effect of the thermal stability (detergent and dispersant) additive has been noted with many other materials.

Fluorosilicone MIL-P-25968 "O"-Rings. The fluorosilicone "O"- ring materials' post physical properties after a 28 day aging in JP-8 and the +100 and +100 X 4 concentrations of fuel additive performed fully satisfactorily at a temperature of 200 ° F as illustrated in Table #5. At temperatures of 250 ° F and 325 ° F, the materials' physical properties were degraded to an unacceptable level in both the JP-8 fuel and in the fuel containing a thermal stability additive in both concentrations as shown in Tables #6 and #7.

Leaded Bronze (TAP MS 285). This material is used for the bearings in gear-driven fuel pumps on aircraft engines. This particular material showed excessive amounts of lead and copper being extracted from the bearing material into the fuel during initial static coupon testing. It was determined that this excessive extraction (depicted in Table #8, graphite furnace element measurements) was caused by improper mixing and by the saw cut surfaces of the coupons. Appropriate mixing and using polished surfaced coupons, which more nearly duplicated the material in use, corrected this excessive extraction of copper and lead. (See Table #9.) The JP-8 baseline fuel and the fuel containing the +100 additive in normal and X 4 concentrations exhibited similar effects.

Due to a concern for this copper and lead being extracted from the leaded bronze alloy material by the fuel, this effect was evaluated in a fuel recirculation test stand using an actual engine fuel pump with bearings of this same material and coatings. The evaluation included baseline JP-8 fuel and fuel containing the thermal stability additives in the X 4 concentrations at a temperature of 325 ° F for approximately 119 hours. The pump was evaluated to determine whether the fuel has resulted in degraded pump performance (measured by pressure and flow changes) and any fuel effects and/or thermal stability additive effects on the bearings and gear wear. Tables #10 and #11 show the performance comparison of the JP-8 effects on the leaded bronze bearing to that of the + 100 fuel x4 concentration (detergent and dispersant) additive. Note the weight delta.

Fuel/Material Selection Guide. As a result of the subject fuels and materials evaluations, acceptable temperature ranges are being established for many of the currently used and new fuel system materials. This list of materials will provide airframe, engine and component manufacturers with a valuable guide in selecting materials which should withstand the temperatures and fuel environments of both current and future aircraft applications.

Conclusions/Findings.

1. On the basis of a comparative evaluation with JP-8 and of the materials tested and evaluated, the Betz/Dearborn 8Q462 thermal stability fuel additive is compatible with the materials found in Air Force aircraft fuel systems.

2. The Betz/Dearborn 8Q462 thermal stability fuel additive actually improves the material properties of many non-metallic materials. In addition, the Betz/Dearborn 8Q462 thermal stability fuel additive generally results in cleaner metallics.

3. Numerous materials were determined to have temperature limitations after continuous exposure at temperature.

4. A fuel selected to be used for a particular fuel additive also should be used as the JP-8 comparative fuel, since different fuels may have significantly different oxidation characteristics.

5. Materials should not be used beyond temperature range. Examples, Fluorosilicone "O" rings, 225 ° F; Fluorocarbon "O" rings, 325 - 400 ° F; (note compression set limits); Nitrile (fuel compatible), 160 ° F.

6. Materials which should not be used in contact with fuel / fuel vapors are: Nitrile, "O" rings designed for hydraulic fluids and Polysulfides potting compounds (e.g. CS-3100).

7. Certain metallic materials should not be used in continuous contact with fuel. These are: copper, lead, zinc, and cadmium.

8. Materials which should be retested in component / application form as appropriate for correlation or results include: leaded bronze, nylon, "O" rings, and Teflon.

9. New research / development programs are needed for certain fuel system materials. These are: extended temperature range (- 45 ° F to 400 ° F) of "O" rings fuel applications; fuel bladder innerliners, 225 ° F minimum; and potting compounds, 225 ° F minimum.

Acknowledgments. This work was supported by the U. S. Air Force, Wright Laboratory, Fuels and Lubrication Division, Aero-Propulsion and Power Directorate, Wright-Patterson Air Force Base, OH under contract No. F33615-92-2207, with Mr. Charles W. Frayne serving as the Air Force Technical Monitor. Support was also provided by the University of Dayton Research Institute, Materials Engineering, Kettering Laboratories and by the Materials Directorate, Wright Laboratory, Wright Patterson Air Force Base, OH.

References:

1. ASTM D4054-81, Fuel Additives
2. ASTM Standard & MIL HDBK 149B, Military Standardization HandBook Rubber
3. ASTM D381, Gums
4. ASTM D3242MoD, Acid No.
5. ASTM D412, Tensile, Elongation
6. ASTM D395 Method B, Compression Set
7. ASTM D2240, Hardness (Pencil)
8. ASTM F483-90, Weight Loss/Gain
9. ASTM G1-90, Cleaning
10. SAE/AS5172, Peel Strength
11. ASTM D257, Resistivity
12. ASTM D790, Laminar Shear
13. FED STD 141, MTHE 6301) Tape Adhesion
14. MIL-S-22473, Torque
15. ASTM D1414, Tensile/Elongation
16. ASTM D2624, Conductivity
17. ASTM G46, Pitting Evaluation
18. ASTM F-995, SCC

TABLE # 1

FUEL / MATERIAL COMPATIBILITY TEST RESULTS

TEST PLAN I.D. NO. I.G.3
TEST TEMPERATURE (°F) 160
EXPOSURE TIME (DAYS) 28
TEST DATE START: 15 FEB 96

MATERIAL / IDENTITY: NITRILE, N 602-70 (PARKER) MIL-P-5315
USE: AIRFRAME, FUEL SYSTEM GASKETS, "O" - RINGS
TEST ADDITIVE/FUEL: BETZ DEARBORN 8Q462 (Normal & x4 Concentrations)/93POSF 2980
JP-8 BASELINE FUEL: 93 POSF 2980 +(JP-8 Additives)

MATERIAL PROPERTY TESTS (AVG. 5 SPECIMENS)	TEST MATERIAL / FUEL EXPOSURE RESULTS			TEST EVALUATION CRITERIA					EVALUATION OF TEST RESULTS					
	JP-8	JP-8 +100	JP8+100 (X4)	CONTROL MAT MEASURED AT AMBIENT TEMP	ALLOWABLE TOLERANCE REQUIREMENT				COMPARISON TO CONTROL & ALLOWABLE REQUIREMENTS			OVERALL EVALUATION		
	POST	POST	POST		DECREASE	MIN VALUE	INCREASE	MAX VALUE	JP-8	JP-8+100	JP-8+100 x4	JP8	+100	X4.
TENSILE (PSI)	1009	1526	1592	1712	25%				-41	-11	-7	O	W	W
ELONGATION (%)	199	199	202	264	25%				-25	-25	-23	W	W	W
VOLUME SWELL (%)	16	17	17	N/A		0%		25%	P	P	P	W	W	W
HARD'S; a) SHORE A (PTS)	57	65	65	66	5 PTS		5 PTS		-3	-3	-4	W	W	W
b) PENCIL														
COMP. SET (avg. 2 spcm's)	9	12	6	N/A				50%	P	P	P	W	W	W
LAP SHEAR (PSI)														
COHESION (%)														
TAPE ADHESION (P/F)														
PEEL STRENGTH (LB/IN)														
LAMINAR SHEAR (PSI)														
RESISTIVITY (OHM-CM)														
TORQUE (INCH -LBS.)														
RUPTURE PRESS. (IN.HG)														
VISUAL OBSERVATIONS														

FUELS PROPERTY TESTS*	TEST FUEL / MATERIAL EXPOSURE 4 X 7 DAY PERIODS (28 DAYS)			CONTROL FUEL PRE (NEW) VS. POST (STRESSED) 160°F 7 DAYS						SPECIFICATION RANGE FOR JP-8		GENERAL OBSERVATIONS		
	JP-8	JP-8 +100	JP8+100 (X4)	JP-8		JP-8 + 100		JP-8 + 100 x4						
	POST	POST	POST	PRE	POST	PRE	POST	PRE	POST	MIN	MAX	JP8	+100	X4
COLOR (7 DAYS)	NE	NE	NE	C	C1	C	C1	C	C1			NE	NE	NE
ACID NO. mgKOH/gm	NE	.004	.004	.001	NE	.001	.002	.003	.003		0.015	NE	NE	NE
GUMS mg/100ml	NE	4.4	41.4	.6	NE	4.4	5.2	9.6	12.4		7	NE	W	W
HYDROPEROXIDES mM/l	NE	0	0	.001	NE	0	.01	0	ND			NE	W	O
CONDUCTIVITY pS/m @72°F	15	400	662	100	NE	248	NE	912	NE	150	600	NE	W	W
VISUAL OBSERVATIONS												O	W	NSR

NOTES:

Fuel Color:	C =	Clear C1 - C6 = Light to Dark
Designations:	NE =	Not Evaluated; ND = Not Detected; BD = Below Detection; P = Pass; F = Fail
	W =	Within Allowable Requirement; O = Outside Allowable Requirement
	OT =	Material Tested Beyond Temperature Range
	N/A =	Not applicable; NSR = No Spec. Req. and/or 4 (x) Additive Concentration

* Fuel Property Test Data Was Collected to Establish Whether Any Correlation Exists Between Material Degradation and Fuel Properties Degradation

DATE:
UDRI TECH: J. DUES
UDRI ENG: B. WILT
UDRI P.I. ENG: D.H. KALT
A.F. AUT. W./MLSE: A. FLETCHER
A.F. AUT. WL/POSF S. A. ANDERSON

TABLE # 2

FUEL / MATERIAL COMPATIBILITY TEST RESULTS

TEST PLAN I.D. NO. I.G.3
TEST TEMPERATURE (°F) 180
EXPOSURE TIME (DAYS) 28
TEST DATE START: 14 MAR 96

MATERIAL / IDENTITY: NITRILE, N 602-70 (PARKER) MIL-P-5315
USE: AIRFRAME, FUEL SYSTEM GASKETS, "O" - RINGS
TEST ADDITIVE/FUEL: BETZ DEARBORN 8Q462 (Normal & x4 Concentrations)/POSF 2980
JP-8 BASELINE FUEL: 93 POSF 2980 +(JP-8 Additives)

MATERIAL PROPERTY TESTS (AVG. 5 SPECIMENS)	TEST MATERIAL / FUEL EXPOSURE RESULTS			TEST EVALUATION CRITERIA					EVALUATION OF TEST RESULTS					
				CONTROL MAT MEASURED AT AMBIENT TEMP	ALLOWABLE TOLERANCE REQUIREMENT				COMPARISON TO CONTROL & ALLOWABLE REQUIREMENTS			OVERALL EVALUATION		
	JP-8	JP-8 +100	JP8+100 (X4)		DECREASE	MIN VALUE	INCREASE	MAX VALUE	JP-8	JP-8+100	JP-8+100 x4	JP8	+100	X4
	POST	POST	POST											
TENSILE (PSI)	1163	1093	1320	1712	25%				-32	-36	-23	OT	OT	W
ELONGATION (%)	232	223	187	264	25%				-12	-16	-29	W	W	O
VOLUME SWELL (%)	18	17	17	N/A		0%		25%	P	P	P	W	W	W
HARD'S; a) SHORE A (PTS)	55	57	62	66	5 PTS		5 PTS		-11	-9	-4	OT	OT	W
b) PENCIL														
COMP. SET (avg. 2 spcm's)	19	24	25	N/A				50%	P	P	P	W	W	W
LAP SHEAR (PSI)														
COHESION (%)														
TAPE ADHESION (P/F)														
PEEL STRENGTH (LB/IN)														
LAMINAR SHEAR (PSI)														
RESISTIVITY (OHM-CM)														
TORQUE (INCH -LBS.)														
RUPTURE PRESS. (IN.HG)														
VISUAL OBSERVATIONS														

FUELS PROPERTY TESTS*	TEST FUEL / MATERIAL EXPOSURE 4 X 7 DAY PERIODS (28 DAYS)			CONTROL FUEL PRE (NEW) VS. POST (STRESSED) 180°F 7 DAYS						SPECIFICATION RANGE FOR JP-8		GENERAL OBSERVATIONS		
	JP-8	JP-8 +100	JP8+100 (X4)	JP-8		JP-8 + 100		JP-8 + 100 x4						
	POST	POST	POST	PRE	POST	PRE	POST	PRE	POST	MIN	MAX	JP8	+100	X4
COLOR (7 DAYS)	C1	C1	C1	C	C1	C	C1	C	C1			W	W	W
ACID NO. mgKOH/gm	.006	.003	.004	.001	.003	.001	.003	.003	.007		0.015	W	W	W
GUMS mg/100ml	3.2	5.4	12.4	.6	6.0	4.4	4.0	9.6	8.4		7	W	W	O
HYDROPEROXIDES mM/l	.37	0	0	.001	ND	0	.022	0	.00			O	W	W
CONDUCTIVITY pS/m @72°F	149	376	604	100	NE	248	NE	912	NE	150	600	W	W	NSR
VISUAL OBSERVATIONS														

NOTES:

Fuel Color:	C =	Clear C1 - C6 = Light to Dark
Designations:	NE =	Not Evaluated; ND = Not Detected; BD = Below Detection; P = Pass; F = Fail
	W =	Within Allowable Requirement; O = Outside Allowable Requirement
	OT =	Material Tested Beyond Temperature Range
	N/A =	Not applicable; NSR = No Spec. Req. and/or 4 (x) Additive Concentration

* Fuel Property Test Data Was Collected to Establish Whether Any Correlation Exists Between Material Degradation and Fuel Properties Degradation

DATE:
UDRI TECH: J. DUES
UDRI ENG: B. WILT
UDRI P.I. ENG: D.H. KALT
A.F. AUT. W./MLSE: A. FLETCHER
A.F. AUT. WL/POSF S. A. ANDERSON

TABLE # 3

FUEL / MATERIAL COMPATIBILITY TEST RESULTS

TEST PLAN I.D. NO. I.G.3
TEST TEMPERATURE (°F) 200
EXPOSURE TIME (DAYS) 28
TEST DATE START: 21 NOV 94
MATERIAL / IDENTITY: NITRILE, N 602-70 (PARKER) MIL-P-5315
USE: AIRFRAME, FUEL SYSTEM GASKETS, "O" - RINGS
TEST ADDITIVE/FUEL: BETZ DEARBORN 8Q462 (Normal & x4 Concentrations)/93POSF 2980
JP-8 BASELINE FUEL: 93 POSF 2980 +(JP-8 Additives)

MATERIAL PROPERTY TESTS (AVG. 5 SPECIMENS)	TEST MATERIAL / FUEL EXPOSURE RESULTS			TEST EVALUATION CRITERIA					EVALUATION OF TEST RESULTS					
				CONTROL MAT MEASURED AT AMBIENT TEMP	ALLOWABLE TOLERANCE REQUIREMENT				COMPARISON TO CONTROL & ALLOWABLE REQUIREMENTS			OVERALL EVALUATION		
	JP-8 POST	JP-8+100 POST	JP8+100 (X4) POST		DECREASE	MIN VALUE	INCREASE	MAX VALUE	JP-8	JP-8+100	JP-8+100 x4	JP8	+100	X4
TENSILE (PSI)	174	991	1211	1970	25%				-91	-50	-39	OT	OT	OT
ELONGATION (%)	34	138	147	265	25%				-87	-48	-45	OT	OT	OT
VOLUME SWELL (%)	16	17	18	N/A		0%		25%	P	P	P	W	W	W
HARD'S; a) SHORE A (PTS)	76	63	63	69	5 PTS		5 PTS		+7	-6	-6	OT	OT	OT
b) PENCIL														
COMP. SET (avg. 2 spcm's)	37	41	40	N/A				50%	P	P	P	W	W	W
LAP SHEAR (PSI)														
COHESION (%)														
TAPE ADHESION (P/F)														
PEEL STRENGTH (LB/IN)														
LAMINAR SHEAR (PSI)														
RESISTIVITY (OHM-CM)														
TORQUE (INCH -LBS.)														
RUPTURE PRESS. (IN.HG)														
VISUAL OBSERVATIONS														

*FUELS PROPERTY TESTS**	TEST FUEL / MATERIAL EXPOSURE 4 X 7 DAY PERIODS (28 DAYS)			CONTROL FUEL PRE (NEW) VS. POST (STRESSED) 200°F 7 DAYS										
										SPECIFICATION RANGE FOR JP-8		GENERAL OBSERVATIONS		
	JP-8	JP-8+100	JP8+100 (X4)	JP-8		JP-8 + 100		JP-8 + 100 x4						
	POST	POST	POST	PRE	POST	PRE	POST	PRE	POST	MIN	MAX	JP8	+100	X4
COLOR (7 DAYS)	NE	NE	NE	C	C1	C	C1	C	C1			NE	NE	NE
ACID NO. mgKOH/gm	NE	NE	NE	.001	.002	.001	.002	.003	.003		0.015	NE	NE	NE
GUMS mg/100ml	NE	NE	NE	2	4.8	4.4	2.8	9.6	8.6		7	NE	NE	NE
HYDROPEROXIDES mM/l	NE	NE	NE	.004	.037	0	.038	0	.018			NE	NE	NE
CONDUCTIVITY pS/m @72°F	NE	NE	NE	108	39	248	131	912	410	150	600	NE	NE	NE
VISUAL OBSERVATIONS														

NOTES:

Fuel Color: C = Clear C1 - C6 = Light to Dark
Designations: NE = Not Evaluated; ND = Not Detected; BD = Below Detection; P = Pass; F = Fail
W = Within Allowable Requirement; O = Outside Allowable Requirement
OT = Material Tested Beyond Temperature Range
N/A = Not applicable; NSR = No Spec. Req. and/or 4 (x) Additive Concentration

* Fuel Property Test Data Was Collected to Establish Whether Any Correlation Exists Between Material Degradation and Fuel Properties Degradation

DATE:
UDRI TECH: J. DUES
UDRI ENG: B. WILT
UDRI P.I. ENG: D.H. KALT
A.F. AUT. W./MLSE: A. FLETCHER
A.F. AUT. WL/POSF S. A. ANDERSON

TABLE # 4

FUEL / MATERIAL COMPATIBILITY TEST RESULTS

TEST PLAN I.D. NO.	I.G.3	MATERIAL / IDENTITY:	NITRILE, N 602-70 (PARKER) MIL-P-5315
TEST TEMPERATURE (°F)	325	USE:	AIRFRAME, FUEL SYSTEM GASKETS, "O" - RINGS
EXPOSURE TIME (DAYS)	28	TEST ADDITIVE/FUEL:	BETZ DEARBORN 8Q462 (Normal & x4 Concentrations)/93POSF 2980
TEST DATE START:	16 NOV 94	JP-8 BASELINE FUEL:	93 POSF 2980 +(JP-8 Additives)

MATERIAL PROPERTY TESTS (AVG. 5 SPECIMENS)	TEST MATERIAL / FUEL EXPOSURE RESULTS			TEST EVALUATION CRITERIA					EVALUATION OF TEST RESULTS					
	JP-8	JP-8 +100	JP8+100 (X4)	CONTROL MAT MEASURED AT AMBIENT TEMP	ALLOWABLE TOLERANCE REQUIREMENT				COMPARISON TO CONTROL & ALLOWABLE REQUIREMENTS			OVERALL EVALUATION		
	POST	POST	POST		DECREASE	MIN VALUE	INCREASE	MAX VALUE	JP-8	JP-8+100	JP-8+100 x4	JP8	+100	X4
TENSILE (PSI)	132	(Broke)	111	1970	25%				-93	-100	-94	OT	OT	OT
ELONGATION (%)	35	(Broke)	23	265	25%				-87	-100	-92	OT	OT	OT
VOLUME SWELL (%)	19	15	15	N/A		0%		25%	P	P	P	W	W	W
HARD'S; a) SHORE A (PTS)	70	82	75	69	5 PTS		5 PTS		+1	+13	+6	W	OT	W
b) PENCIL														
COMP. SET (avg. 2 spcm's)	170	162	147	N/A				50%	F	F	F	OT	OT	OT
LAP SHEAR (PSI)														
COHESION (%)														
TAPE ADHESION (P/F)														
PEEL STRENGTH (LB/IN)														
LAMINAR SHEAR (PSI)														
RESISTIVITY (OHM-CM)														
TORQUE (INCH -LBS.)														
RUPTURE PRESS. (IN.HG)														
VISUAL OBSERVATIONS														

*FUELS PROPERTY TESTS**	TEST FUEL / MATERIAL EXPOSURE 4 X 7 DAY PERIODS (28 DAYS)			CONTROL FUEL PRE (NEW) VS. POST (STRESSED) 325°F 7 DAYS						SPECIFICATION RANGE FOR JP-8		GENERAL OBSERVATIONS		
	JP-8	JP-8 +100	JP8+100 (X4)	JP-8		JP-8 + 100		JP-8 + 100 x4						
	POST	POST	POST	PRE	POST	PRE	POST	PRE	POST	MIN	MAX	JP8	+100	X4
COLOR (7 DAYS)	C2	C2	C2	C	C2	C	C2	C	C2			W	W	W
ACID NO. mgKOH/gm	.005	.001	.006	.001	.007	.001	.006	.003	.008		0.015	W	W	W
GUMS mg/100ml	4.2	7.6	15.8	2	3	4.4	3.4	9.6	12.2		7	W	O	O
HYDROPEROXIDES mM/l	.016	NE	.011	.004	.017	0	.015	0	.008			O	NE	O
CONDUCTIVITY pS/m @72°F	10.75	99	403	108	123	248	141	912	555	150	600	W	W	W
VISUAL OBSERVATIONS														

NOTES:

Fuel Color: C = Clear C1 - C6 = Light to Dark

Designations:
NE = Not Evaluated; ND = Not Detected; BD = Below Detection; P = Pass; F = Fail
W = Within Allowable Requirement; O = Outside Allowable Requirement
OT = Material Tested Beyond Temperature Range
N/A = Not applicable; NSR = No Spec. Req. and/or 4 (x) Additive Concentration

* Fuel Property Test Data Was Collected to Establish Whether Any Correlation Exists Between Material Degradation and Fuel Properties Degradation

DATE:
UDRI TECH: J. DUES
UDRI ENG: B. WILT
UDRI P.I. ENG: D.H. KALT
A.F. AUT. W./MLSE: A. FLETCHER
A.F. AUT. WL/POSF S. A. ANDERSON

TABLE # 5

FUEL / MATERIAL COMPATIBILITY TEST RESULTS

TEST PLAN I.D. NO.: I.G.5 / II.G.2
TEST TEMPERATURE (°F): 200
EXPOSURE TIME (DAYS): 28
TEST DATE START: 9 JUN 94
MATERIAL / IDENTITY: FLUOROSILICONE, PARKER L 677, MIL-P-25988
USE: AIRFRAME, FUEL SYSTEM GASKETS, "O" - RINGS
TEST ADDITIVE/FUEL: BETZ DEARBORN 8Q462 (Normal & x4 Concentrations)/93POSF 2980
JP-8 BASELINE FUEL: 93 POSF 2980 +(JP-8 Additives)

MATERIAL PROPERTY TESTS (AVG. 5 SPECIMENS)	TEST MATERIAL / FUEL EXPOSURE RESULTS			TEST EVALUATION CRITERIA					EVALUATION OF TEST RESULTS					
	JP-8	JP-8 +100	JP8+100 (X4)	CONTROL MAT MEASURED AT AMBIENT TEMP	ALLOWABLE TOLERANCE REQUIREMENT				COMPARISON TO CONTROL & ALLOWABLE REQUIREMENTS			OVERALL EVALUATION		
	POST	POST	POST		DECREASE	MIN VALUE	INCREASE	MAX VALUE	JP-8	JP-8+100	JP-8+100 x4	JP8	+100	X4
TENSILE (PSI)	856	857	852	984	45%				-13	-13	-13	W	W	W
ELONGATION (%)	199	201	194	231	35%				+2	+3	-1	W	W	W
VOLUME SWELL (%)	9	9	9	N/A		0%		25%	P	P	P	W	W	W
HARD'S; a) SHORE A (PTS)	63	63	63	69	20Pts				-2	-2	-2	W	W	W
b) PENCIL														
COMP. SET (avg. 2 spcm's)	6	9	10	N/A				30%	P	P	P	W	W	W
LAP SHEAR (PSI)														
COHESION (%)														
TAPE ADHESION (P/F)														
PEEL STRENGTH (LB/IN)														
LAMINAR SHEAR (PSI)														
RESISTIVITY (OHM-CM)														
TORQUE (INCH -LBS.)														
RUPTURE PRESS. (IN.HG)														
VISUAL OBSERVATIONS														

FUELS PROPERTY TESTS*	TEST FUEL / MATERIAL EXPOSURE 4 X 7 DAY PERIODS (28 DAYS)			CONTROL FUEL PRE (NEW) VS. POST (STRESSED) 200°F 7 DAYS										
	JP-8	JP-8 +100	JP8+100 (X4)	JP-8		JP-8 + 100		JP-8 + 100 x4		SPECIFICATION RANGE FOR JP-8		GENERAL OBSERVATIONS		
	POST	POST	POST	PRE	POST	PRE	POST	PRE	POST	MIN	MAX	JP8	+100	X4
COLOR (7 DAYS)	C1	C1	C1	C	C1	C	C1	C	C1			W	W	W
ACID NO. mgKOH/gm	.002	.002	.003	.001	.002	.001	.002	.003	.003		0.015	W	W	W
GUMS mg/100ml	3.4	5.2	14.2	2	4.8	4.4	2.8	9.6	8.6		7	W	W	W
HYDROPEROXIDES mM/l	.09	.03	0	.004	.037	0	.038	0	.018			O	W	W
CONDUCTIVITY pS/m @72°F	42	231	399	108	39	248	131	912	410	150	600	W	W	W
VISUAL OBSERVATIONS														

NOTES:

Fuel Color:	C =	Clear C1 - C6 = Light to Dark
Designations:	NE =	Not Evaluated; ND = Not Detected; BD = Below Detection; P = Pass; F = Fail
	W =	Within Allowable Requirement; O = Outside Allowable Requirement
	OT =	Material Tested Beyond Temperature Range
	N/A =	Not applicable; NSR = No Spec. Req. and/or 4 (x) Additive Concentration

* Fuel Property Test Data Was Collected to Establish Whether Any Correlation Exists Between Material Degradation and Fuel Properties Degradation

DATE:
UDRI TECH: J. DUES
UDRI ENG: B. WILT
UDRI P.I. ENG: D.H. KALT
A.F. AUT. W./MLSE: A. FLETCHER
A.F. AUT. WL/POSF S. A. ANDERSON

FUEL / MATERIAL COMPATIBILITY TEST RESULTS

TEST PLAN I.D. NO.	II.G.2	MATERIAL / IDENTITY:	FLUOROSILICONE, L677 PARKER, MIL-R-25988
TEST TEMPERATURE (°F)	250	USE:	ENGINE / AIRFRAME, FUEL SYSTEMS GASKET
EXPOSURE TIME (DAYS)	28	TEST ADDITIVE/FUEL:	Betz/Dearborn 8Q462 ((Normal and x4 Concentrations) /93 POSF 2980
TEST DATE START:	20 JUN '95	JP-8 BASELINE FUEL:	92 POSF 2980 + (JP-8 Additives)

MATERIAL PROPERTY TESTS (AVG. 5 SPECIMENS)	TEST MATERIAL / FUEL EXPOSURE RESULTS			TEST EVALUATION CRITERIA					EVALUATION OF TEST RESULTS					
	JP-8	JP-8 +100	JP8+100 (X4)	CONTROL MAT MEASURED AT AMBIENT TEMP	ALLOWABLE TOLERANCE REQUIREMENT				COMPARISON TO CONTROL & ALLOWABLE REQUIREMENTS			OVERALL EVALUATION		
	POST	POST	POST		DECREASE	MIN VALUE	INCREASE	MAX VALUE	JP-8	JP-8+100	JP-8+100x4	JP8	+100	X4
TENSILE (PSI)	162	546	562	984	45%				-84	-45	-43	OT	W	W
ELONGATION (%)	130	225	192	195	35				-33	+15	-2	W	W	W
VOLUME SWELL (%)	4	9	8	N/A		0		25	P	P	P	W	W	W
HARD'S; a) SHORE A (PTS)	44	54	58	65	20				-21	-11	-7	OT	W	W
b) PENCIL														
COMP. SET (%) (avg. 2 spcm's)	18	NT	NT	N/A				30	P	NE	NE	W	NE	NE
LAP SHEAR (PSI)														
COHESION (%)														
TAPE ADHESION (P/F)														
PEEL STRENGTH (LB/IN)														
LAMINAR SHEAR (PSI)														
RESISTIVITY (OHM-CM)														
TORQUE (INCH -LBS.)														
RUPTURE PRESS. (IN.HG)														
VISUAL OBSERVATIONS														

*FUELS PROPERTY TESTS**	TEST FUEL / MATERIAL EXPOSURE 4 X 7 DAY PERIODS (28 DAYS)			CONTROL FUEL PRE-NEW) VS. POST (STRESSED) 250°F 7 DAYS						SPECIFICATION RANGE FOR JP-8		GENERAL OBSERVATIONS		
	JP-8	JP-8 +100	JP8+100 (X4)	JP-8		JP-8 + 100		JP-8 + 100 x4						
	POST	POST	POST	PRE	POST	PRE	POST	PRE	POST	MIN	MAX	JP8	+100	X4
COLOR (7 DAYS)	NE	NE	NE	C	C1	C	C1	C	C1			NE	NE	NE
ACID NO. mgKOH/gm	NE	NE	NE	.001	.002	.003	.003	.003	.002		0.015	NE	NE	NE
GUMS mg/100ml	NE	NE	NE	.6	3.6	4.0	4	9.6	6.4		7	NE	NE	NE
HYDROPEROXIDES mM/l	NE	NE	NE	.001	.01	.22	.01	0	.01			NE	NE	NE
CONDUCTIVITY pS/m @72°F	NE	NE	NE	100	NE	248	NE	912	NE	150	600	NE	NE	NE
VISUAL OBSERVATIONS														

NOTES:

Fuel Color: C = Clear C1 - C6 = Light to Dark

Designations:
N.E. = Not Evaluated; N.D. = Not Detected; B. D. = Below Detection; P = Pass; F = Fail
W = Within Allowable Requirement; O = Outside Allowable Requirement
OT = Material Tested Beyond Temperature Range
N/A = Not applicable; NSR = No Spec. Req. and/or 4 (x) Additive Concentration

* Fuel Property Test Data Was Collected to Establish Whether Any Correlation Exists Between Material Degradation and Fuel Properties Degradation

DATE:	
UDRI TECH:	J. DUES
UDRI ENG:	B. WILT
UDRI P.I. ENG:	D.H. KALT
A.F. AUT. W./MLSE:	A. FLETCHER
A.F. AUT. WL/POSF	S. A. ANDERSON

TABLE # 7

FUEL / MATERIAL COMPATIBILITY TEST RESULTS

TEST PLAN I.D. NO.	II.G.2/I.G.5	**MATERIAL / IDENTITY:**	FLUOROSILICONE "O" RING 1677 PARKER, MIL-R-25988
TEST TEMPERATURE (°F)	325	**USE:**	ENGINE COMPONENTS
EXPOSURE TIME (DAYS)	28	**TEST ADDITIVE/FUEL:**	Betz/Dearborn 8Q462 ((Normal and x4 Concentrations) /93 POSF 2980
TEST DATE START:	7 SEPT '94	**JP-8 BASELINE FUEL:**	93 POSF 2980 + (JP-8 Additives)

MATERIAL PROPERTY TESTS (AVG. 5 SPECIMENS)	TEST MATERIAL / FUEL EXPOSURE RESULTS			TEST EVALUATION CRITERIA					EVALUATION OF TEST RESULTS					
	JP-8	JP-8 +100	JP8+100 (X4)	CONTROL MAT MEASURED AT AMBIENT TEMP	ALLOWABLE TOLERANCE REQUIREMENT				COMPARISON TO CONTROL & ALLOWABLE REQUIREMENTS			OVERALL EVALUATION		
	POST	POST	POST		DECREASE	MIN VALUE	INCREASE	MAX VALUE	JP-8	JP-8+100	JP-8+100x4	JP8	+100	X4
TENSILE (PSI)	121	131	139	896	45%				-86	-85	-84	OT	OT	OT
ELONGATION (%)	88	96	82	214	35				-59	-55	-62	OT	OT	OT
VOLUME SWELL (%)	11	10	10	N/A		0		25	P	P	P	W	W	W
HARD'S; a) SHORE A (PTS)	38	40	41	67	20				-29	-27	-26	OT	OT	OT
b) PENCIL														
COMP. SET (%) (avg. 2 spcm's)	60	60	57	N/A				30	F	F	F	OT	OT	OT
LAP SHEAR (PSI)														
COHESION (%)														
TAPE ADHESION (P/F)														
PEEL STRENGTH (LB/IN)														
LAMINAR SHEAR (PSI)														
RESISTIVITY (OHM-CM)														
TORQUE (INCH -LBS.)														
RUPTURE PRESS. (IN.HG)														
VISUAL OBSERVATIONS														

*FUELS PROPERTY TESTS**	TEST FUEL / MATERIAL EXPOSURE 4 X 7 DAY PERIODS (28 DAYS)			CONTROL FUEL PRE-NEW) VS. POST (STRESSED) 325°F 7 DAYS						SPECIFICATION RANGE FOR JP-8		GENERAL OBSERVATIONS		
	JP-8	JP-8 +100	JP8+100 (X4)	JP-8		JP-8 + 100		JP-8 + 100 x4						
	POST	POST	POST	PRE	POST	PRE	POST	PRE	POST	MIN	MAX	JP8	+100	X4
COLOR (7 DAYS)	C3	C3	C3	C	C2	C	C2	C	C2			W	W	W
ACID NO. mgKOH/gm	.003	.010	.004	.001	.007	.001	.006	.003	.008		0.015	W	W	W
GUMS mg/100ml	12.0	13.6	20.0	2	3	4.4	3.4	9.6	12.2		7	O	O	O
HYDROPEROXIDES mM/l	.025	.001	NE	.004	.017	O	.015	0	.008			O	W	NE
CONDUCTIVITY pS/m @72°F	343	1011	627	108	123	248	141	912	555	150	600	W	O	W
VISUAL OBSERVATIONS														

NOTES:

Fuel Color:	C =	Clear C1 - C6 = Light to Dark
Designations:	N.E. =	Not Evaluated; N.D. = Not Detected; B. D. = Below Detection; P = Pass; F = Fail
	W =	Within Allowable Requirement; O = Outside Allowable Requirement
	OT =	Material Tested Beyond Temperature Range
	N/A =	Not applicable; NSR = No Spec. Req. and/or 4 (x) Additive Concentration

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TABLE # 8

FUEL / MATERIAL COMPATIBILITY TEST RESULTS

TEST PLAN I.D. NO. II.M.23.1
TEST TEMPERATURE (°F) 325
EXPOSURE TIME (DAYS) 28
TEST DATE START: 7 SEP 94

MATERIAL / IDENTITY: LEADED BRONZE (TAP MS 285), SAW CUT
USE: ENGINE FUEL PUMP GEAR BEARING
TEST ADDITIVE/FUEL: Betz Dearborn 8Q462 (Normal and x4 Concentrations) /93 POSF 2980
JP-8 BASELINE FUEL: 93 POSF 2980 + (JP-8 Additives)

MATERIAL PROPERTY TESTS (AVG. 5 SPECIMENS)	TEST MATERIAL / FUEL EXPOSURE RESULTS						EVALUATION OF TEST RESULTS			
	JP-8		JP-8 +100		JP8+100 (X4)		*OBSERVATIONS AND REFERENCES*	OVERALL EVALUATION		
	PRE	POST	PRE	POST	PRE	POST		JP8	+100	X4
COLOR	L	L3	L	L3	L	L3	Discoloration / Surface Deposits All Samples	CN	W	W
PITTING (VISUAL)	ND	P	ND	P	ND	P		CN	W	W
PITTING (MICROSCOPY)	ND	P	ND	P	ND	P	Pitting All Samples	CN	W	W
AVG. WT. (gms)	14.8183	14.8123	15.0083	15.0061	16.0856	16.0818				
GAIN / LOSS (gms)		-.0010		-.0022		-.0038				
MICROSCOPY EVAL.										

*FUELS PROPERTY TESTS**	TEST FUEL / MATERIAL EXPOSURE 4 X 7 DAY PERIODS (28 DAYS)						CONTROL FUEL PRE (NEW) VS. POST (STRESSED 7 DAYS @ 325°F)						SPEC. RANGE FOR JP-8	TEST RESULTS GENERAL OBSERVATIONS		
							JP-8		JP-8 + 100		JP-8 + 100 x4					
	7	28	7	28	7	28	PRE	POST	PRE	POST	PRE	POST	MIN / MAX	JP8	+100	X4
COLOR (7 DAYS)	C5	C5	C4	C4	C3	C3	C	C1	C	C1	C	C1		W	W	W
CONDUCTIVITY (AVG. of 4)	PRE	POST	PRE	POST	PRE	POST										
PS/M AT 72° F	104	6	227	97	764	480	108	123	248	141	912	555	150/600	O	O	W
GRAPHITE FURN/ICP (PPB)	7 DAY	28 DAY	7 DAY	28 DAY	7 DAY	28 DAY										
Cu	500	550	1800	800	3000	1200								O	O	O
Pb	2000	ND	7000	ND	10,000	ND								O	O	O
Sn	ND	ND	ND	ND	ND	ND								W	W	W

NOTES:

Metallic Color:	L =	*Light (No Deposit)*	L1 - L2 = *Discoloration/Deposits*		
Fuel Color:	C =	*Clear*	C1 - C6 = Light to Dark		
Designations:	NE =	*Not Evaluated;*	ND = *Not Detected;*	BD = *Below Detection*	P = *Pitting*
Comparisons:	W =	*Within Allowable Requirement;*			
	OT =	*Material Tested Beyond Temperature Range*	O = *Outside Allowable Requirement*		
	N/A =	*Not applicable;*	CN = *Control*		
	GT =	*Greater than 500 ppb*	LT = *Less than 500 ppb*		
	NSR =	*No Spec. Req. and/or 4 (x) Additive Concentration*			

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METALLICS

TABLE # 9

FUEL / MATERIAL COMPATIBILITY TEST RESULTS

TEST PLAN I.D. NO.	II.M.23.2	MATERIAL / IDENTITY:	LEADED BRONZE (TAP MS 285), Cu, POLISHED EXCEPT D.F. END
TEST TEMPERATURE (°F)	325	USE:	ENGINE FUEL PUMP GEAR BEARING
EXPOSURE TIME (DAYS)	28	TEST ADDITIVE/FUEL:	Betz Dearborn 8Q462 (Normal and x4 Concentrations) /93 POSF 2980
TEST DATE START:	7 SEP 94	JP-8 BASELINE FUEL:	93 POSF 2980 + (JP-8 Additives)

MATERIAL PROPERTY TESTS (AVG. 5 SPECIMENS)	TEST MATERIAL / FUEL EXPOSURE RESULTS						EVALUATION OF TEST RESULTS			
	JP-8		JP-8 +100		JP8+100 (X4)		*OBSERVATIONS AND REFERENCES*	OVERALL EVALUATION		
	PRE	POST	PRE	POST	PRE	POST		JP8	+100	X4
COLOR	L	L2	L	L2	L	L2		W	W	W
PITTING (VISUAL)	ND	NOTE	ND	NOTE	ND	NOTE	Voids in Graphite Coating - All Fuels	W	W	W
PITTING (MICROSCOPY)	ND	ND	ND	ND	ND	ND	EDS Mapping Revealed Selective Leaching of Pb	CN	W	W
AVG. WT. (gms)	14.7343	14.7347	14.7221	14.7216	14.8250	14.8246	Not Present, No Noticeable effect on Cu or Sn			
GAIN / LOSS (gms)		+.0004		-.0005		-.0004		W	W	W
MICROSCOPY EVAL.										

*FUELS PROPERTY TESTS**	TEST FUEL / MATERIAL EXPOSURE 4 X 7 DAY PERIODS (28 DAYS)						CONTROL FUEL PRE (NEW) VS. POST (STRESSED 7 DAYS @ 325°F)						SPEC. RANGE FOR JP-8	TEST RESULTS GENERAL OBSERVATIONS		
							JP-8		JP-8 + 100		JP-8 + 100 x4					
	7	28	7	28	7	28	PRE	POST	PRE	POST	PRE	POST	MIN / MAX	JP8	+100	X4
COLOR (7 DAYS)	C2	C2	C2	C2	C2	C2	C	C1	C	C1	C	C1		W	W	W
CONDUCTIVITY (AVG. of 4)	PRE	POST	PRE	POST	PRE	POST										
PS/M AT 72° F	105	9	442	35	751	334	108	39	248	131	912	410	150/600	O	W	W
GRAPHITE FURN/ICP (PPB)	7 DAY	28 DAY	7 DAY	28 DAY	7 DAY	28 DAY										
Cu	127	NE	130	NE	145	NE								W	W	W
Pb	565	NE	540	NE	620	NE								O	O	O
Sn	47	NE	53	NE	45	NE								W	W	W

NOTES:

Metallic Color:	L = *Light (No Deposit)*	L1 - L2 = *Discoloration/Deposits*	
Fuel Color:	C = *Clear*	C1 - C6 = Light to Dark	
Designations:	NE = *Not Evaluated;*	ND = *Not Detected;*	BD = *Below Detection* P = *Pitting*
Comparisons:	W = *Within Allowable Requirement;*		
	OT = *Material Tested Beyond Temperature Range*		O = *Outside Allowable Requirement*
	N/A = *Not applicable;*		CN = *Control*
	GT = *Greater than 500 ppb*		LT = *Less than 500 ppb*
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METALLICS

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Table #10

LABORATORY TEST STAND ENGINE GEAR PUMP BEARING TEST EVALUATION COMPARISON RESULTS

119 HOURS @ 325°F

	JP-8	JP-8 + 100 x4 (BETZ)
OVERALL PUMP PERFORMANCE *(FLOW)*	SOME FLOW LOSS (starting conditions)	NO DISCERNIBLE FLOW LOSS
GEARS *(2 EACH)*	CLEAN	VERY CLEAN
BEARINGS (LEADED BRONZE) *(4 EACH)*	SOME WEAR	MINIMUM WEAR

TABLE #11

GEAR PUMP BEARINGS

BEARING WEIGHT CHART

PUMP MODEL 828200
S/N EX-1046
(USED FOR TESTING)
325°F / 119 HOURS

TYPE OF TEST	*BEARING SERIAL NO.*	*PRE-TEST WEIGHT-GRAMS*	*POST-TEST WEIGHT-GRAMS*	*BEARING WEIGHT DELTA*	*DATE WEIGHED*
JP-8 BASELINE	00004	336.288	336.269	- .019	6 / 20 /95 AND 9 / 11 / 96
JP-8 BASELINE	00004B	337.319	337.298	- .021	
JP-8 BASELINE	00014	367.003	366.964	- .039	
JP-8 BASELINE	00001	367.645	367.548	- .097	
JP-8 + BETZ X4	00005	336.774	336.770	- .004	9 / 11 96 AND 11 / 18 / 96
JP-8 + BETZ X4	00009	336.559	336.556	- .003	
JP-8 + BETZ X4	00007	366.888	366.891	+ .003	
JP-8 + BETZ X4	00002	367.423	367.417	- .006	