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Recent Trends in Aviation Turbine Fuel Properties

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Summary

This report is an examination of published inspection data, obtained from Department of Energy (and predecessor agency) reports, covering 743 samples of Jet A aviation turbine fuel for the 12-year period 1969–80. The statistics in this report cover 22 properties that form the detailed requirements of the commercial specifications for Jet A fuel. Data output includes plots and tables of the distribution of property values, average and extreme values, the probability of properties approaching their specification limits, and the trends of all of these with time.

Annual average values of aromatics content, mercaptan sulfur content, distillation temperature at 10 percent recovered, smoke point, and freezing point showed small but recognizable trends toward their specification limits. Near-specification property values are defined as those values that approach their specification limits within a standard precision range of reproducibility. Most reported fuels had one to three near-specification properties, none more than five. About 20 percent of the overall samples for the 12-year survey had no near-specification properties, but this fraction decreased from 37 percent in 1969 to 10 percent in 1980. As expected, aromatics content, smoke point, and freezing point were by far the most common near-specification properties. Such important properties as total sulfur content, flashpoint, density, heat of combustion, and thermal stability were almost never near specification. Selected comparisons of property statistics showed good agreement with data furnished through the courtesy of United Airlines, Inc.

Introduction

This report presents a survey of aviation turbine fuel properties taken from published inspection reports for the purpose of determining representative and extreme property values and their trends with time.

Limited and costly crude oil supplies and shifts in competing product demands may make it advantageous to refine aviation turbine (jet) fuels with broader boiling-range and compositional tolerances. These fuels very likely will have property changes that may require relaxation of some specification limits (refs. 1 to 5). Previous papers have already noted a trend in the aromatics hydrocarbon content of jet fuels, which in the past decade or more has been increasing toward its maximum specification value (refs. 4 and 6).

The relationship of specified variations in aviation turbine fuel properties to the overall characteristics and refining yield of these fuels is demonstrated by the results of refinery-model computer programs. In a previous study, Flores (ref. 7) reported the calculated yields of aviation fuel as functions of the distillation temperature (final boiling point), hydrogen content, and freezing point of the fuel. Exxon researchers (refs. 8 and 9) reported calculated yields as functions of flashpoint and freezing point. Dickson and Karvelas of Bonner & Moore, in a study concentrating on military fuels (refs. 10 and 11), supplemented calculations by an extensive questionnaire survey of refiners, to obtain subjective estimates of the influence of property variations on yield.

The study presented in this report is a more thorough review of turbine properties than previous single-property assessments or theoretical refinery-model calculations. The property compilations cover 743 samples of Jet A aviation turbine fuel from Department of Energy (and predecessor agency) fuel inspection reports for the 12-year period 1969–80. Reference 12, the latest survey covered, was published in March 1981. The fuel sample characteristics are reported by refineries through a cooperative agreement between the American Petroleum Institute and the Department of Energy (DOE). The fuel sample data are as reported, and each sample does not necessarily represent the same volume share of the total domestic fuel-refining output. Nevertheless, the DOE regards the reported fuel samples and their values as close reflections of the average quality of fuel supplied by United States refiners. For a few properties, this report also includes values from a large fuel inspection data bank maintained by United Airlines, Inc. (ref. 13). Additional fuel data were furnished by P. P. Campbell and M. P. Hardy of United Airlines.

This report summarizes distributions, averages, and trends of the properties that form the requirements for the commercial specification of Jet A aviation turbine fuel. An important element in this study is the relationship of the reported fuel properties to their specification-limit requirements. This is analyzed by a study of those property values that lie within a band defined as near specification. A condensation of key findings of this report, based on data up to 1979, has been published by the author as part of a Society of Automotive Engineers symposium (ref. 14).

Aviation Turbine Fuel Properties and Requirements

The current requirements for commercial aviation turbine fuel are contained in the American Society for Testing and Materials (ASTM) standard D 1655-81 (ref. 15). This is a voluntary standard, but it is the specification used for almost all supply and usage of commercial aviation turbine fuel in the United States and some foreign countries.

Table I lists the requirements of ASTM D 1655-81 for Jet A aviation turbine fuel by property and specification limit. Jet A, a kerosine type of petroleum distillate product, constitutes, for practical purposes, the total usage of commercial aviation turbine fuel in the United States. Jet A–1 fuel, not included in table I, differs from Jet A only in a maximum freezing point limit of −47° C (−50° C prior to 1980), as compared with −40° C for Jet A. Refining of Jet A–1 has been negligible in this country since 1975, but the fuel is still in common use in Europe and elsewhere for international service. Another fuel excluded from table I, Jet B, is an entirely different wide-distillation-range fuel, resembling the common military JP–4. There has been essentially no domestic refining of Jet B since 1977.

Twenty-two properties are listed in table I, constituting 21 separate specification requirements. The specifications also require the reporting of intermediate distillation temperatures at 50 and 90 vol% recovered, but there are otherwise no limitations on these temperatures for Jet A. Combustion properties are defined by either of two smoke-point limits, depending on the naphthalene content of the fuel, or alternatively by a luminometer measurement. With the exception of density, which is specified by minimum and maximum limits, the specifications are single limited. Properties may deviate to any extent in the permissible direction from their specification limits. The specification limits, therefore, do not necessarily define a representative, or average fuel. More information on fuel characteristics and their significance can be found in other sources (ref. 16).

Fuel property data in this report were taken from Department of Energy (and predecessor agency) annual reports from 1969 (then published by the U.S. Bureau of Mines) to 1980 (ref. 12). Each report presents property data for 54 or more Jet A samples. The 12-year period of study thus includes most of the era of present Jet A usage and provides a large sample population for statistical treatment.

The annual DOE inspection reports each list 33 to 36 fuel characteristics. As shown in table I, all of the properties necessary for the ASTM requirements are covered in the inspection reports.

Distribution of Property Values

Summary of Distribution Plots

The distribution of property values for 15 of the Jet A properties listed in table I is presented in the form of histograms, or bar graphs. Each histogram consists of the accumulated values for 1969 to 1980 from the DOE inspection data (ref. 12). The histograms plot the probability, or fraction of total sample population, for discrete property value intervals represented by bars. A few of the properties in table I, such as distillation loss and residue, were excluded from this treatment because they are more or less qualitative or limited in range. All of the table I properties were included in subsequent analyses, however.

The histograms are shown in figures 1 to 15. In addition, table II is a summary of parameters defining central values and ranges for each property described by the histograms. For the accumulated 1969 to 1980 data, the table lists the number of samples for each property, the mean, the standard deviation, and the 5-, 50-, and 95-percentile values. Although the total survey constituted 743 samples, not all fuels had complete characterizations; hence many properties have less than the maximum number of samples. The mean and the standard deviation are the usual quantities used in statistical analysis. For a normal, Gaussian distribution of values (only a fair approximation for many of the fuel properties), a range of plus and minus one standard deviation about the mean brackets 68 percent of the samples. The percentile values define representative fuel property values that may be useful to designers: the 5-percentile value is an expected minimum, excluding arbitrarily the lowest 5 percent extremes; the 50-percentile value is the most probable; the 95-percentile value is an expected maximum, excluding the highest extremes. The percentile values were calculated from the summation of the probabilities of the histograms, interpolating within the discrete bar intervals as required. The 50 percentile is of course the median value, which would be identical to the mean for a normal distribution. Discrepancies between the means and medians in table II are noteworthy indicators of the skewness of property distributions.

Distribution of Values of Selected Properties

Seven properties of Jet A fuel were denoted as selected properties because their values showed significant changes with time or their values have appreciable probabilities near the specification limits. The selected properties are aromatics content, mercaptan sulfur content, distillation temperature at 10 percent recovered, final boiling point, flashpoint, and freezing point. The distributions of selected property values are discussed first and in more detail than those of other property values.

Aromatics content.—The aromatics content is the fraction of fuel composition composed of the benzene type of hydrocarbons or their substituted derivatives. As a class, aromatics have low hydrogen content and thus have the undesirable combustion properties of high flame luminosity and smokiness. Fuels with higher aromatics content also have solubility characteristics that degrade the material properties of many seals and elastomers.

Figure 1 shows the distribution for the accumulated data on Jet A aromatics content. For this histogram, the DOE inspection data were assembled into discrete intervals of 1 vol% each. The most probable interval is

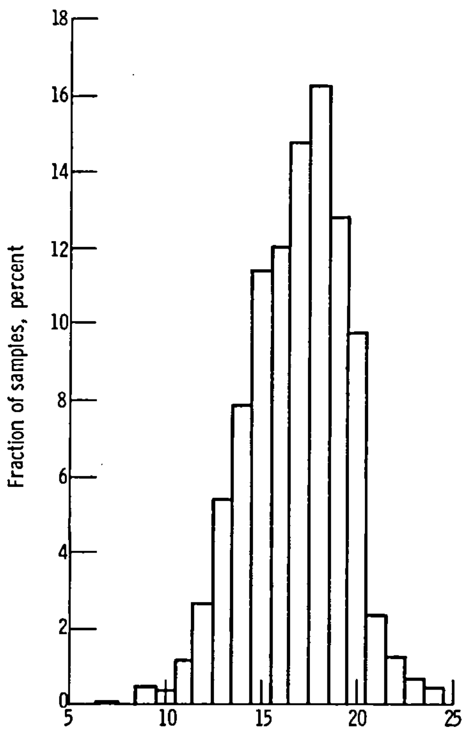


Figure 1. - Distribution of Jet A aromatics content - 1969-80 inspection data.

centered at 18 vol%. Table II shows that the mean aromatics content was 16.8 vol%, and the representative minimum, median, and maximum values (5, 50, and 95 percentiles) were 12.5, 17.2, and 20.5 vol%, respectively. The specification limit for aromatics content of Jet A fuel is 20 vol% maximum; however, contents to 25 vol% are permissible when reported as such by the supplier. Thus the representative maximum aromatics content fuel, with 20.5 vol%, would fall into the "reportable" category. The aromatics content distribution plotted in figure 1 is reasonably symmetrical, and the mean and median values are nearly identical.

Mercaptan sulfur content. – The mercaptan sulfur content is the fraction of fuel composition associated with organic compounds that have sulfur-hydrogen group substitutions. Mercaptans impart a disagreeable odor to fuels and have poor compatibility with some elastomers and metals.

Figure 2 shows the distribution for the accumulated data on Jet A mercaptan sulfur content. For this histogram, the DOE inspection data were assembled into discrete intervals of 0.0001 wt% each. The distribution is unsymmetrical. The majority of the samples had very low mercaptan contents, but the histogram covers a complete range of values from those approaching zero to a few samples beyond the specification limit of 0.003 wt% maximum (not shown in fig. 2).

Many of the inspection samples reported mercaptan sulfur content to only one significant figure. Hence the distribution would show clustering at certain values (0.0010, 0.0020, and 0.0030) in the second decade. For example, round-off of measurements in the range 0.0005 to 0.0015 causes a high probability of measurements reported as merely 0.001. For better representation, the histogram presented in figure 2 was adjusted by dividing the second-decade probabilities reported at 0.0010, 0.0020, and 0.0030 percent into ten 0.0001 intervals each, according to the general trend of the histogram.

Table II shows that the mean mercaptan sulfur content was 0.0007 wt%, and the representative minimum, median, and maximum values were approximately zero, 0.0005, and 0.0020 wt%, respectively. These values were calculated from the original data, without the adjustments made in the construction of the histogram. However, only the maximum value would be affected if calculated from the grouped histogram. The mean and median values do not agree. The higher mean value is weighted by the large values of the low-probability outlying data. The data compilation excludes one sample from the DOE inspection data with an out-of-range and uncertain mercaptan sulfur content of 0.0100 wt%.

Distillation temperatures. – Distillation temperature is the vapor temperature measured in a laboratory still for stated fractions vaporized. For Jet A, specification limits are defined for 10 percent vaporized and final boiling point (100 percent vaporized). The 10-percent limit controls the lower-boiling-point fuel constituents, which influence the fuel volatility; the final boiling point controls the higher-boiling-point constituents, which influence freezing point and other properties.

Figure 3 shows the distribution for the accumulated data on distillation temperature at 10 percent recovered, and figure 4 plots the distribution on final boiling point.

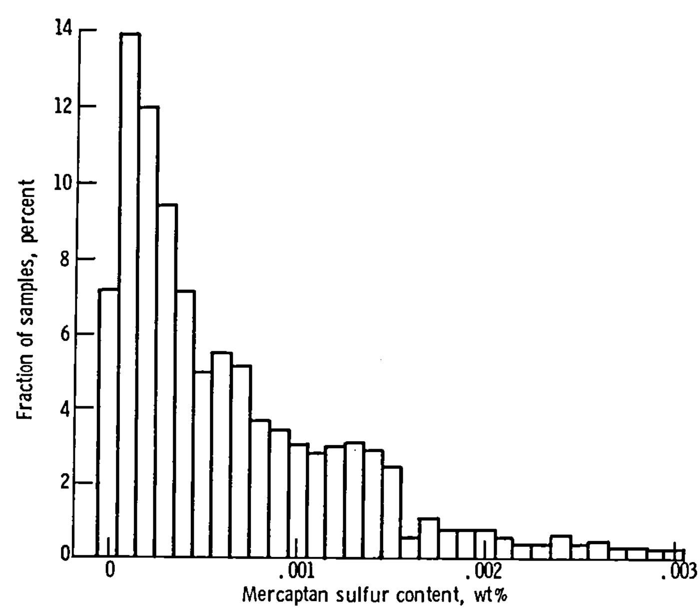


Figure 2. - Distribution of Jet A mercaptan sulfur content - 1969-80 inspection data.

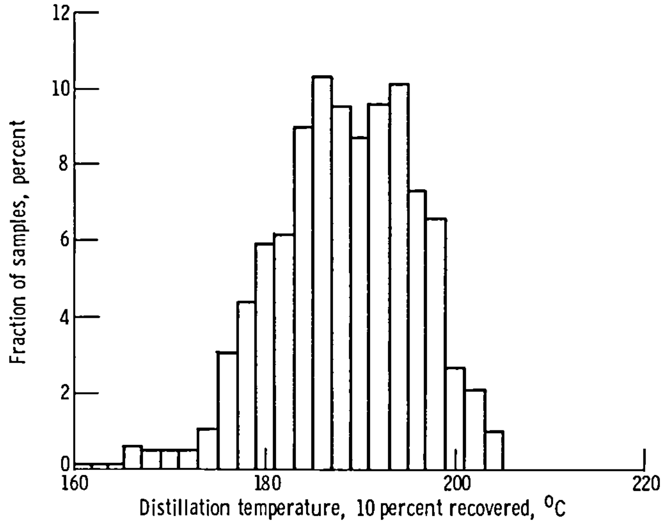


Figure 3. - Distribution of Jet A distillation temperature at 10 percent recovered - 1969-80 inspection data.

For both plots, the DOE data, reported in degrees Fahrenheit, were converted to degrees Celsius and assembled into discrete intervals of 2° C each. Both properties have maximum-limit specifications. For the 10-percent distillation, the limit is 204° C (400° F); and for the final boiling point, it is 300° C (572° F). About 1 percent of the samples for 10-percent distillation were at the specification maximum. None of the final-boiling-point samples was at the specification limit, but the wide range of values extended to below 220° C at the low end. Before 1974, the final-boiling-point limit was 288° C. Only one sample lies between the old limit and the present limit of 300° C.

Table II shows that for distillation temperature at 10 percent recovered, the mean value was 188° C (371° F), and the representative minimum, median, and maximum values were 176° C (349° F), 189° C (371° F), and 199° C (391° F), respectively. For the final boiling point the mean value was 267° C (513° F), and the representative minimum, median, and maximum values were 253° C (486° F), 268° C (515° F), and 281° C (539° F), respectively. Thus the representative maximum final boiling point was still well below the specification limit.

Flashpoint. – The flashpoint is the minimum temperature for ignition of vapors above a liquid sample. The specification limit controls the flammability for safety in handling and to some extent the amount of altitude boiloff losses.

Figure 5 presents the distribution for the accumulated data on flashpoint. For this histogram, the DOE inspection data were converted from Fahrenheit to Celsius and assembled into discrete intervals of 1 degree each. The most probable interval is centered at 52° C. The flashpoint distribution is nearly symmetrical, ranging from the specification limit of 38° C (just one sample) to a few samples near 70° C. Table II shows that the mean flashpoint was 54° C (129° F) and the representative minimum, median, and maximum values were 46° C (114° F), 53° C (128° F), and 63° C (146° F), respectively. Thus the representative minimum-flashpoint fuel had a flashpoint well above the specification limit.

Smoke point. – The smoke point is the maximum flame height achieved in a standard lamp apparatus without smoking. It is a practical measurement of the combustion quality of the fuel. Higher values of smoke point imply more smoke-free combustion.

Figure 6 shows the distribution for the accumulated data on smoke point. For this histogram the DOE inspection data were assembled into discrete intervals of 1 mm each. These intervals conform to the precision of most measurements, although some samples report fractional smoke-point values. The small number of intervals in the histogram produces a coarse, poorly defined histogram. Table II shows that the mean smoke point was 23 mm and the representative minimum, median, and maximum values were 20, 23, and 26.5 mm, respectively. Although the specification limit for smoke point is 20 mm minimum, measurements to 18 mm are

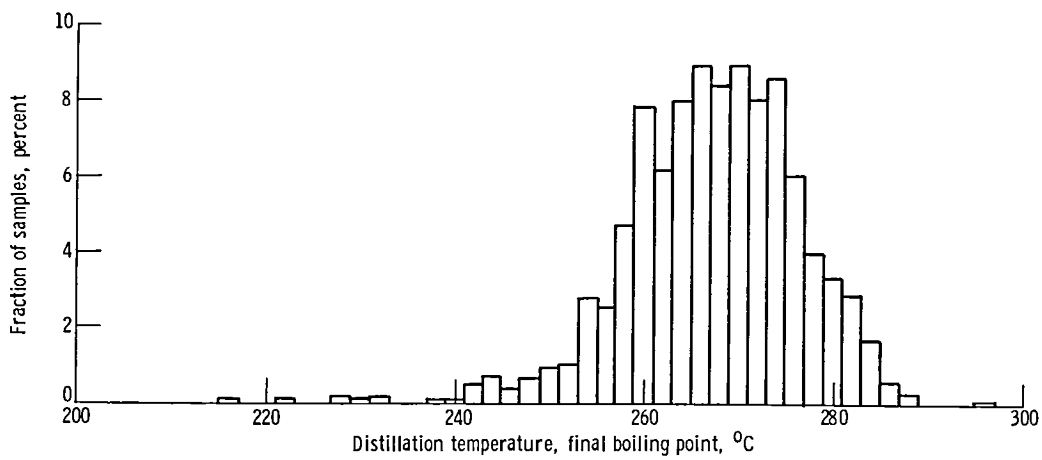


Figure 4. - Distribution of Jet A final boiling point - 1969-80 inspection data.

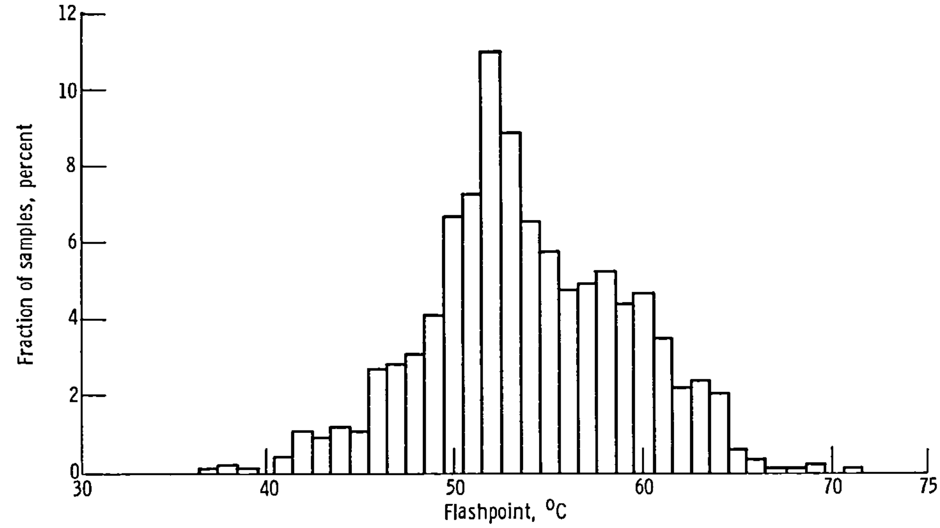


Figure 5. - Distribution of Jet A flashpoint - 1969-80 inspection data.

permissible if reported by the supplier. Only a few sample smoke points were found in the "reportable" range, but the representative minimum smoke point is at the standard specification limit.

Freezing point. – The standard measurement of freezing point is actually a melting point, that is, the temperature at which solid crystals, or wax, disappear upon warming of fuel after the appearance of solids. Freezing-point control is important in maintaining the flowability of aviation fuels at the low temperatures encountered in high-altitude flight.

Figure 7 plots the distribution for the accumulated data on freezing point. For the histogram the DOE inspection data were converted from Fahrenheit to Celsius and assembled into discrete intervals of 1 degree each. The freezing-point distribution is heavily concentrated near the specification limit of –40° C, although there are some samples ranging to very low values. The most probable interval is centered at –42° C, but there is a secondary peak at –48° C. The few samples above –40° C are not off specification; they originate from years prior to 1973 when the limit was –38° C.

Table II shows that the mean freezing point was

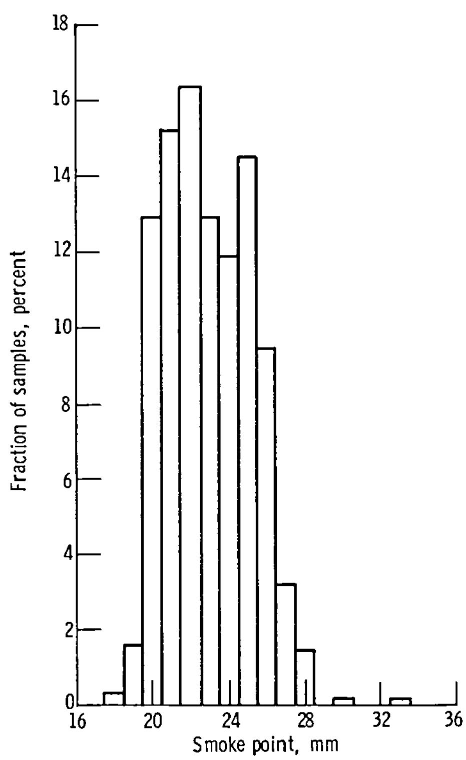


Figure 6. - Distribution of Jet A smoke point - 1969-80 inspection data.

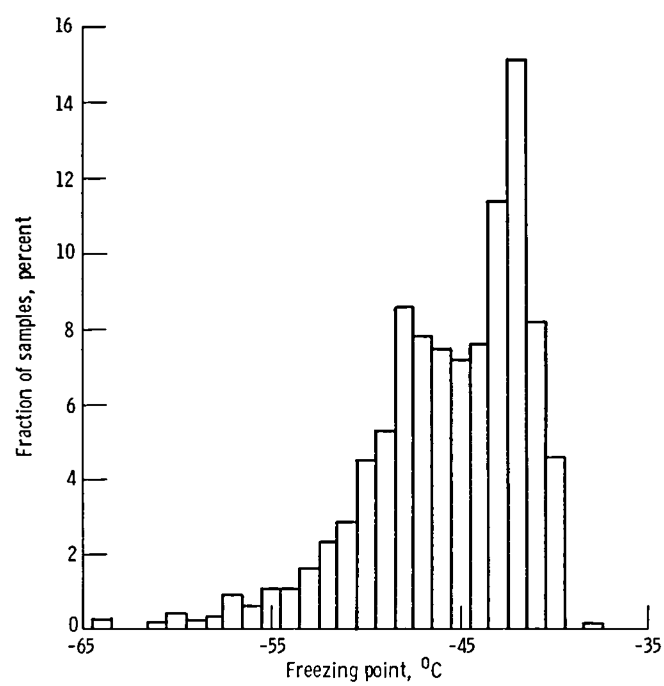


Figure 7. - Distribution of Jet A freezing point - 1969-80 inspection data.

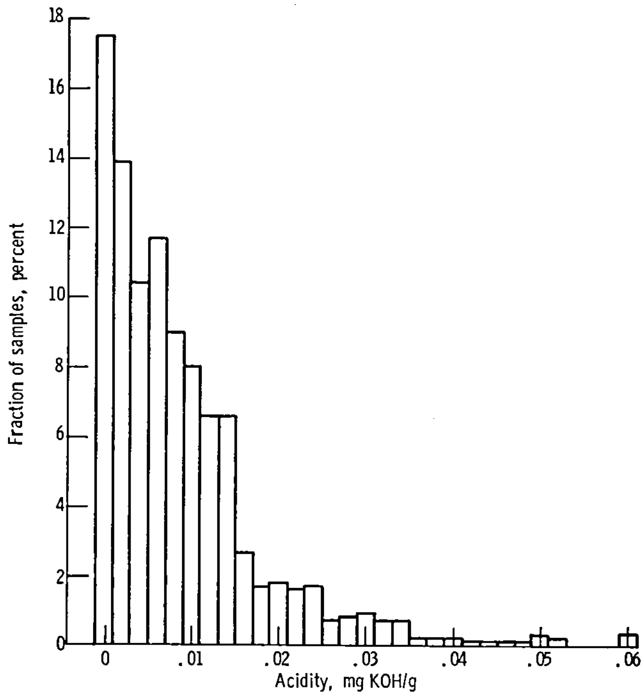


Figure 8. - Distribution of Jet A total acidity - 1969-80 inspection data.

−46° C and the representative maximum, median, and maximum values were −54°, −45°, and −40° C, respectively. Thus the representative maximum-value fuel is at the specification limit for freezing point. The mean value is lower than the median because of the weighting by the extreme low values of some outlying samples.

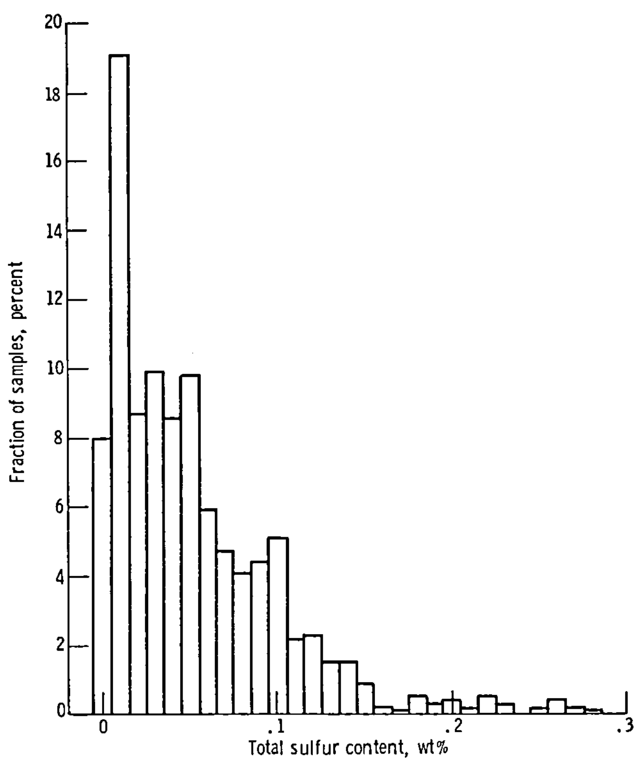


Figure 9. - Distribution of Jet A total sulfur content - 1969-80 inspection data.

The freezing point distribution is most unusual in its extreme skewness and in the existence of two peak probabilities. It appears that the two modes (most common probabilities) result from superimposed distributions. The lower value distribution may represent fuel samples with refining limits imposed by high aromatics contents or poor smoke points, properties associated generally with compositions having low freezing points. The higher value distribution may be associated with samples where freezing point itself dictates the refining limits. Plots of several subsets of the freezing-point distribution (high aromatics, low aromatics, and other groups) showed a tendency toward distributions that confirm this hypothesis, but there was much statistical scatter. These plots were neither sufficiently illustrative nor conclusive to be included in this report.

Distribution of Values of Other Properties

Histograms for eight other properties are plotted in figures 8 to 15, and summaries of central and representative values are included in table II. The distributions of these properties are discussed briefly here.

Figure 8 shows the distribution for acidity. The most probable interval is that centered near zero, and probabilities decrease nearly uniformly with decreasing acidity. Since acidity data are reported usually to only one significant figure, the data for 0.010 to 0.050 acidity were divided into weighted values for interpolated 0.002 subintervals, a treatment similar to that explained for mercaptan sulfur content (fig. 2). Table II lists the mean acidity value as 0.010 mg KOH/g. Figure 8 omits a few outlying values above 0.060 to 0.140 in order to keep the

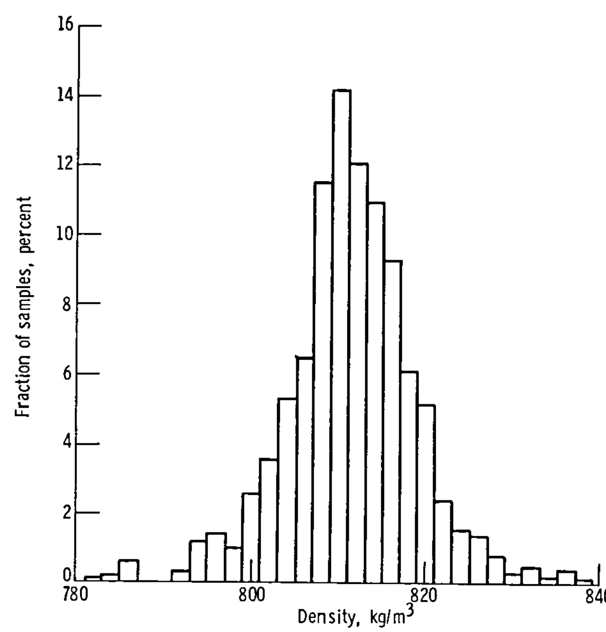


Figure 10. - Distribution of Jet A density - 1969-80 inspection data.

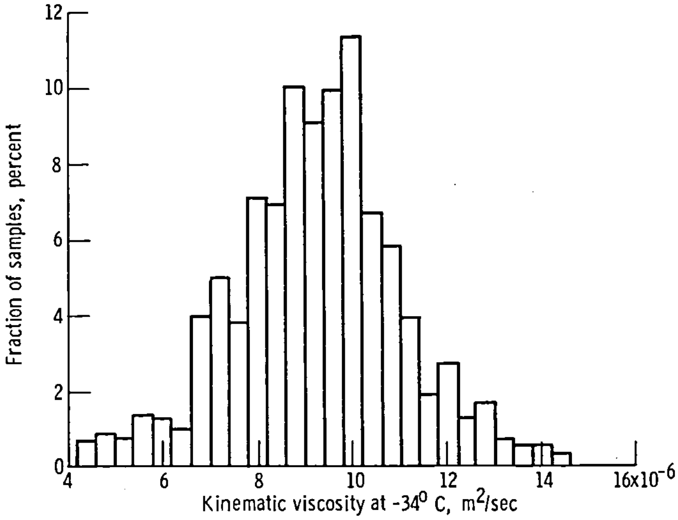


Figure 11. - Distribution of Jet A kinematic viscosity reported at -34° C - 1969-80 inspection data.

figure compact. Three samples in the inspection data with acidities of 0.300 to 0.500, well above the specification limit of 0.100 maximum, were excluded as out of range and possibly erroneous.

Figure 9 presents the distribution for total sulfur content, an analysis of all sulfur constituents in the fuel, including the separately reported mercaptans. The most probable values are those in the interval centered at 0.01 wt%. The distribution resembles that of mercaptan sulfur content (fig. 2), and again the dividing technique was used to spread the data reported at the second-decade values of 0.10 and 0.20 wt%. Mean sulfur content was 0.05 wt%, and there were no samples at the specification maximum of 0.30 wt%.

Figure 10 plots the distribution for density. Density is at present the one property defined by both minimum, 775 kg/m^3, and maximum, 840 kg/m^3, specification limits for Jet A. The distribution is nearly symmetrical. The mean value was 811 kg/m^3 (42.9° API). No sample had a value near the low limit, and very few approached the high limit.

Figure 11 shows the distribution for kinematic viscosity. The viscosity specification for Jet A was changed in 1978 from a reference temperature of −34° C (−30° F) to −20° C (−4° F). The implementation of this change is not complete, and even the latest DOE inspection report (ref. 12) retains the former reference temperature. The specification limit for viscosity is 8×10^{-6} m^2/sec (8 cS) maximum at −20° C. This value was converted from 15×10^{-6} m^2/sec at −34° C on the basis of cooperative laboratory viscosity comparisons. Since it is not possible to make an accurate conversion of intermediate viscosity values without additional data, this report retains the old reference temperature to conform to the DOE values. The distribution for kinematic viscosity is symmetrical. The mean value was 9.2 cS, and no sample was at the specification limit. One sample in the inspection data with a viscosity of nearly 80 cS was excluded as out of range and questionable.

Figure 12 is the distribution for net heat of combustion. The discrete intervals of 0.02 MJ/kg (about 10 Btu/lb) are very small, reflecting the narrow range of this property. The distribution is nearly symmetrical, and no samples were at the specification limit of 42.8 MJ/kg (18 400 Btu/lb) minimum. Mean heat of combustion was 43.23 MJ/kg (18 590 Btu/lb). This data compilation excluded three samples with reported heats of 45.5 to 46.7 MJ/kg, impossible values for hydrocarbon fuels. Very likely these values were uncorrected gross heats of combustion.

Figure 13 presents the distribution for naphthalenes content. There is no specification limit for naphthalenes in Jet A, but naphthalenes above 3 vol% affect the combustion quality of the fuel and require more stringent smoke-point limits (table I). Mean naphthalenes content

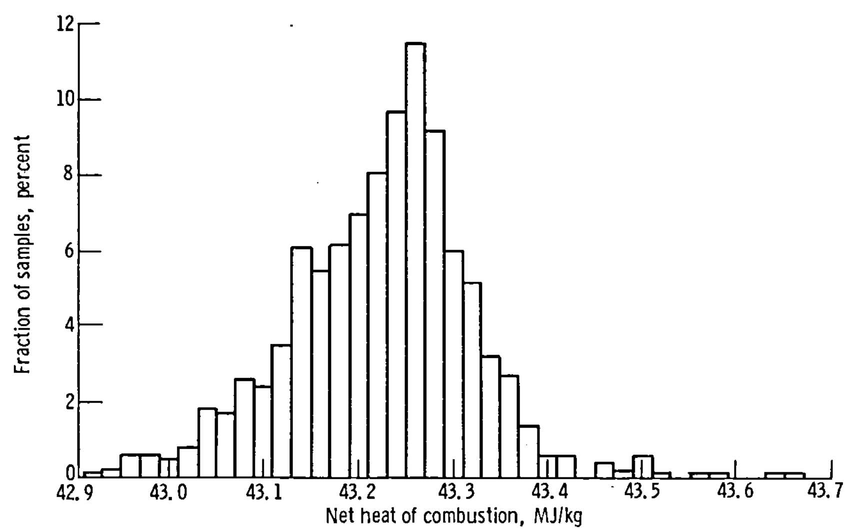


Figure 12. - Distribution of Jet A net heat of combustion - 1969-80 inspection data.

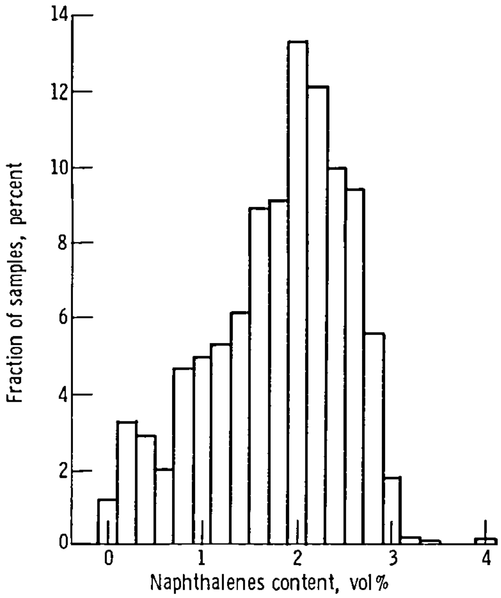


Figure 13. - Distribution of Jet A naphthalenes content - 1969-80 inspection data.

was 1.8 and values of 3 vol% and above were rare.

Figure 14 plots the distribution for one of the criteria for thermal stability, the coker pressure drop. The histogram has discrete intervals of 0.4 kPa, converted from the reported DOE data in inches of mercury. The pressure drop, measured across a filter in the test apparatus, is a determination of suspended degradation products in the fuel. Figure 14 indicates that most of the

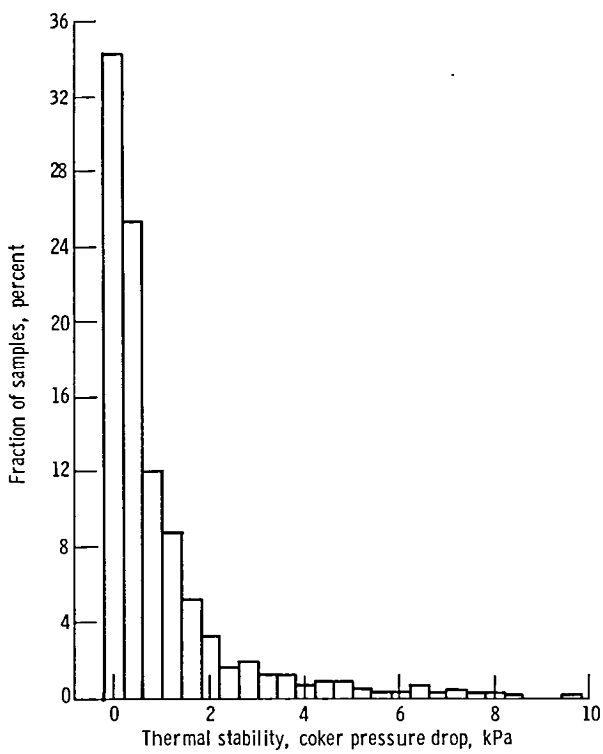


Figure 14. - Distribution of Jet A thermal stability measured by coker filter pressure drop - 1969-80 inspection data.

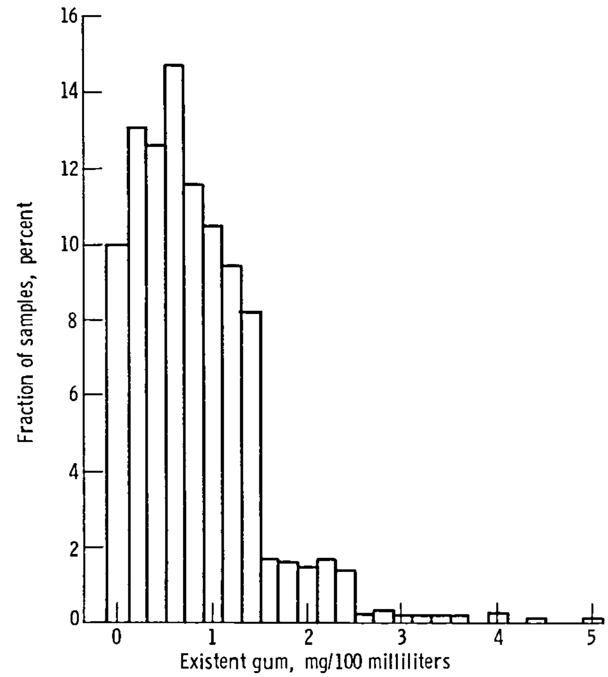


Figure 15. - Distribution of Jet A existent gum by steam evaporation at 232° C - 1969-80 inspection data.

samples have values near zero and only one sample value approaches the specification limit of 10 kPa (3 in. Hg). The mean value of 1 kPa is probably a most unrepresentative central value for the highly skewed distribution. A second thermal stability criterion is based on the color of deposits on a heated tube surface exposed to the fuel. These ratings are expressed as integers from 0 to 4. This limited range of deposit code values is not sufficient for representation by a histogram. The Jet A requirements permit an alternative thermal stability method, the jet fuel thermal oxidation tester, and an alternative, quantitative tube deposit rating, but these are not included in the DOE inspection data. Angello and Bradley (ref. 17) discuss the correlation of tube deposit code numbers and quantitative ratings.

Figure 15 shows the distribution for existent gum, as determined by steam evaporation at 232° C. These data are usually reported to one significant figure, and values reported at 1 to 4 mg per 100 milliters were divided about the surrounding fractional intervals by using the same data treatment discussed for mercaptan sulfur content. The mean value for existent gum was 0.8 mg per 100 milliliters, and no values approach the specification limit of 7 mg per 100 milliliters.

Time-Related Changes

The histograms of figures 1 to 15 are collections of 12 years of inspection data that provide a large statistical population of values but give no indication of possible annual changes in the property value distributions.

Annual property value distributions were examined in addition to the overall 12-year distributions, and a few

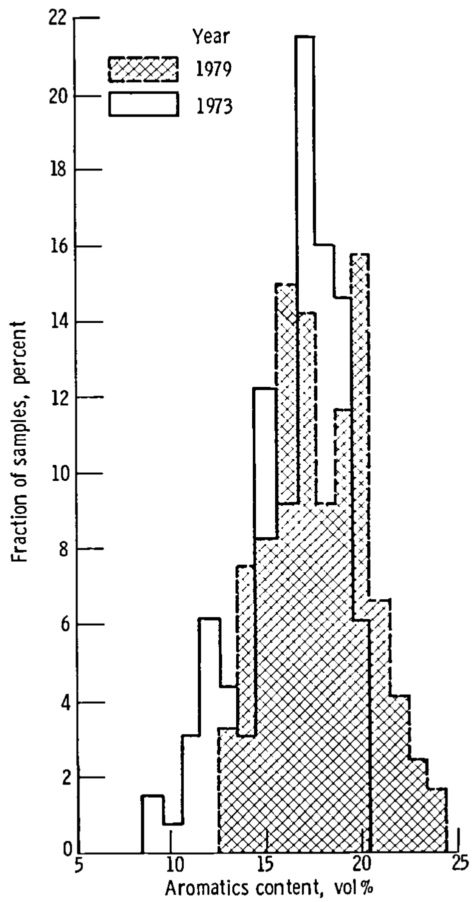


Figure 16. - Comparison of distributions of Jet A aromatics content for inspection data of two years.

examples are presented here. Figure 16 compares the aromatics content distribution reported for 1973 (open bars) and 1979 (shaded bars). The two histograms are superimposed in the figure for comparison. Each is based on 60 to 65 samples and shows more nonuniformity of probabilities than the overall histogram of figure 1. The shift in aromatics values from 1973 to 1979 is evident; the mean increased from 16.3 to 17.9 vol%. The general range of values for both years was nearly the same, however, and both the standard deviations were around 2.5 percent.

Figure 17 compares two freezing-point distributions: 1974 (open bars) and 1979 (shaded bars). These superimposed histograms were purposely selected to illustrate a large variation in mean freezing point, from −46.3° C in 1974 to −43.3° C in 1979. The distributions are difficult to interpret and show a great variation in probabilities from interval to interval. Nevertheless, each histogram bears some resemblance to the unusual shape of the overall histogram of figure 7, with a double peak of most probable intervals. The ranges of the histogram in figure 17 are nearly the same, with a standard deviation of 4.1° C for 1974 and 4.5° C for 1979.

Although the other annual histograms of the Jet A inspection data are not plotted in this report, a summary of representative and central values is given in table III for the year 1980. These were the most recent data at the time this report was written. Table III is thus analogous to table II, except that the summary is for the latest year rather than for the accumulation of 12 years. Mean values in table III are the same as those already included in the 1980 inspection data report (ref. 12). Differences between the values in the tables II and III can be observed. The time trends of property data are discussed further in the following section.

Median Property Values and Their Trends

Changes in Jet A Specification Limits

Assessment of the trends of Jet A property values must take into account the changes in Jet A requirements that occurred during the 12-year period of examination. The specification changes have been small but may have some significance in their influence on the affected property. Table IV summarizes the changes. The limits for freezing point and thermal stability have been altered in the direction of more stringent requirements. The change in viscosity is a redefinition of the test temperature. (The earlier temperature was used in this study to conform to the inspection reports.) The other property-limit changes

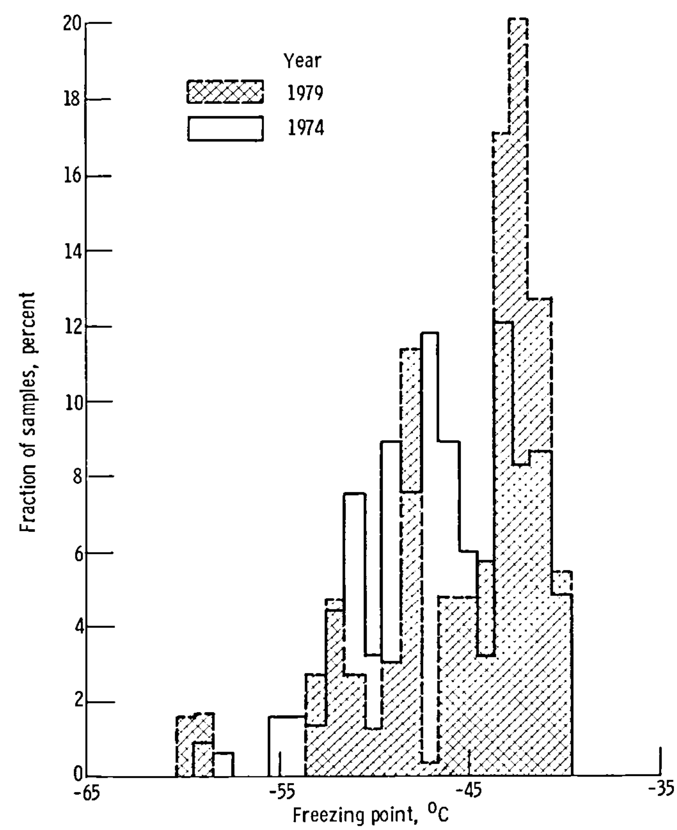
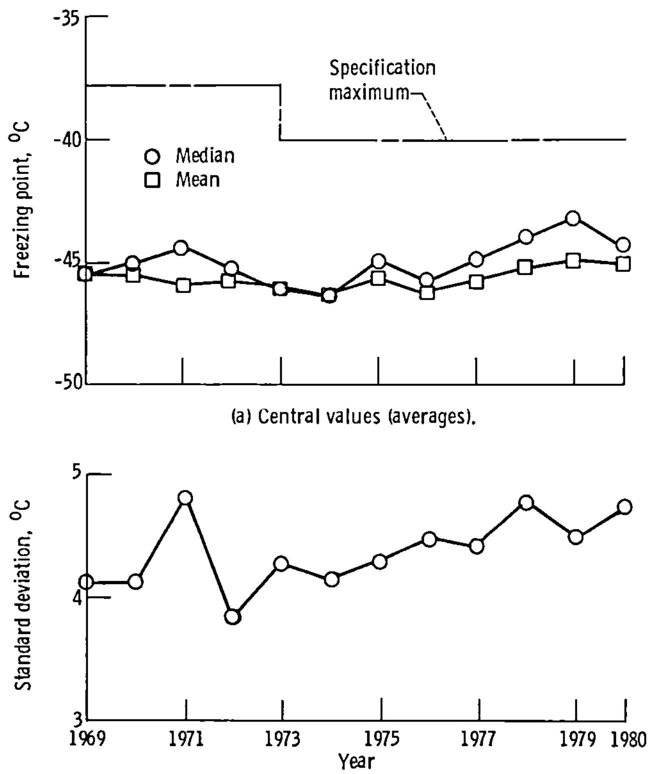


Figure 17. - Comparison of distributions of Jet A freezing point for inspection data of two years.



(a) Central values (averages).

(b) Range indicators (standard deviation).

Figure 18. - Trends of Jet A freezing-point data range and central values - 1969-80 inspection data.

were in the direction of more relaxed specification requirements.

Trends of Range and Central Value

Freezing point provides a good example of the range and central-value trends for the selected Jet A properties. Figure 18 shows for freezing point both the annual mean and median variations on one plot and the annual standard deviation on a separate plot. The mean and median values often diverged by as much as 2° C. The mean was generally lower, or further from the specification limit, being weighted by the low-probability samples that have very low freezing points (fig. 7). Standard deviation, a measurement of range, varied little during the 12-year period of study, but did increase slightly in recent years. The oscillations during 1971 and 1972 are unexplained.

Figures 19 to 32 present the annual trends of central values for the properties described by the histograms of figures 1 to 15. Only the plots for the median are shown (except for aromatics). The median is probably more representative of an average value because it is less influenced by low-probability outlying values than the mean. Generally there was little difference between the median and mean; but where there was a deviation, the median tended to be more conservative, approaching the specification limit more closely (note fig. 18). Each plot shows data points for yearly medians, connected by line segments for illustration, although interpolated values between years have no significance. Appropriate specification limits are indicated by broken lines. Each property value ordinate is scaled to represent relative changes in medians that are consistent with the scaling used for histogram intervals.

Trends of Selected Properties

Examination of figure 18(a) shows that the median freezing point of Jet A decreased appreciably in 1973 and 1974, possibly as a result of the lowering of the specification limit. Since then, median freezing point has increased, reaching a peak of −43.3° C in 1979. The most recent year, 1980, shows a 1° C drop in freezing point, for at least a temporary reversal of the trend. The margin between the median freezing point and the specification limit is relatively small.

Aromatics content (fig. 19) has increased almost uniformly over the period of interest from 16 vol% in 1969 to around 17.8 vol% in the latest 4 years. Figure 19 also includes the trend of mean values as well as medians for comparison to previous surveys of aromatics (refs. 4 and 6). The mean values showed a trend similar to that of the medians, but the means were generally a few tenths of a percent lower. The trend in median aromatics content was an increase toward the 20-percent specification limit, although the "reportable" limit relaxation (footnote a, table I) offers considerable leeway for further increases. The increase in average aromatic content of fuel deliveries was obviously a major factor in instituting this specification provision.

Median mercaptan sulfur content (fig. 20) showed an increasing trend, ranging from 0.00023 wt% in 1969 to 0.00064 wt% in 1980. Although this is a relatively large increase, even the highest median value is only one-fifth of the specification limit. Median 10-percent distillation temperature (fig. 21) also increased with time, from

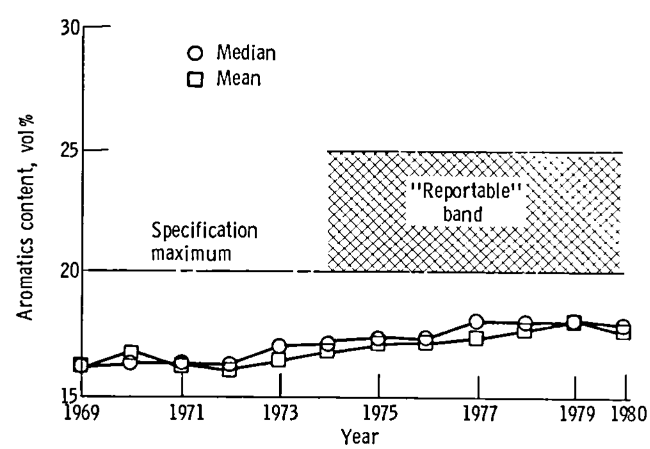


Figure 19. - Trends of mean and median Jet A aromatics content - 1969-80 inspection data.

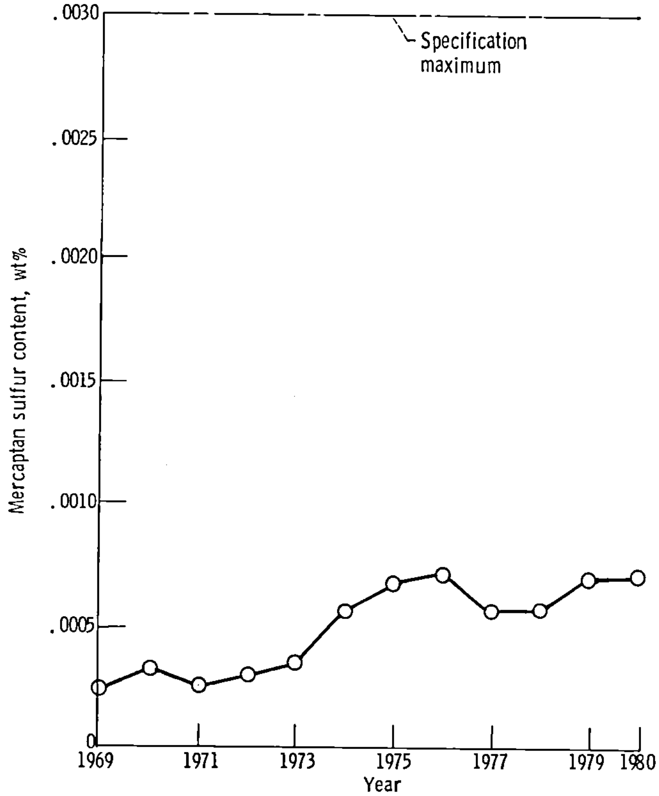


Figure 20. - Trends of median Jet A mercaptan sulfur content - 1969-80 inspection data.

187° C in 1969 to 192° C in 1980. The increase was most noticeable in the last 3 years. Median final boiling point (fig. 22) shows considerable variation but no apparent trend with time. A relaxation of the specification maximum in 1974 had no influence on the yearly median values. Median flashpoint (fig. 23) showed an irregular, increasing trend from 52° C in 1969 to a peak of 56° C in 1978. In this case, the trend was away from the specification limit, and flashpoint is unique among the selected properties in this respect.

The trend in median smoke points (fig. 24) was a slow

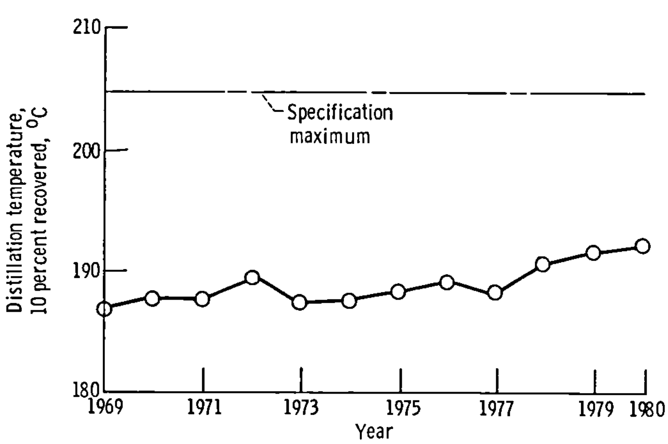


Figure 21. - Trends of median Jet A distillation temperature at 10 percent recovered - 1969-80 inspection data.

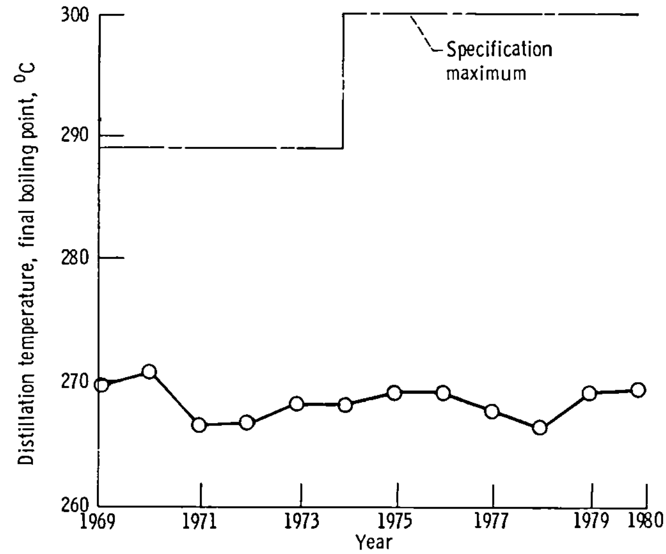


Figure 22. - Trends of median Jet A final boiling point - 1969-80 inspection data.

decrease toward the minimum specification limit, from 23 mm in 1969 to 22 mm at present. Although this change appears relatively small, it is significant, representing a change of a full integer unit in the median. As with

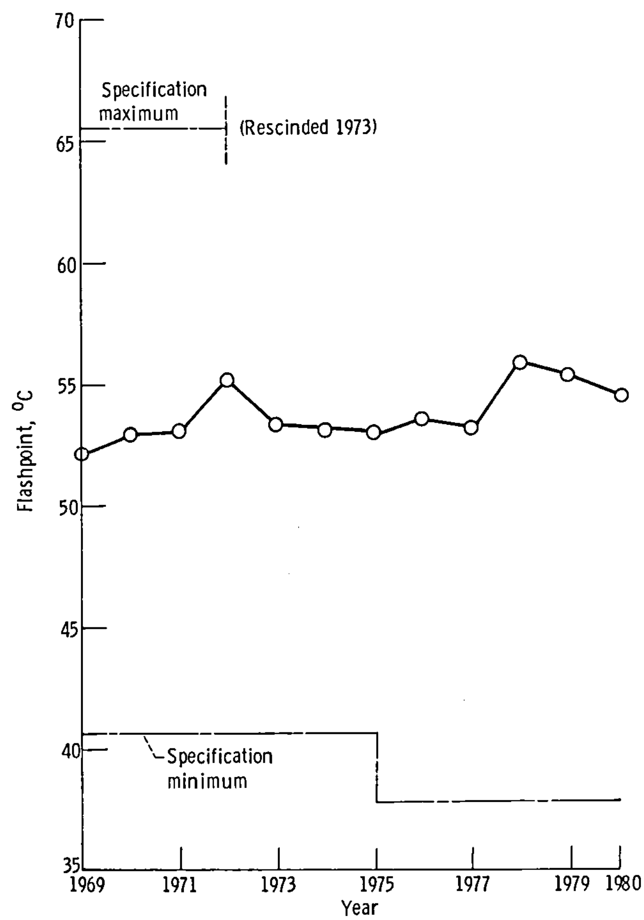


Figure 23. - Trends of median Jet A flashpoint - 1969-80 inspection data.

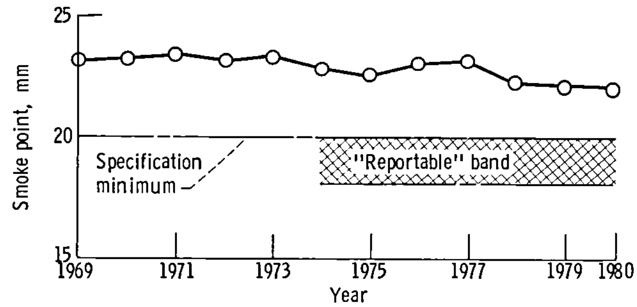


Figure 24. - Trends of median Jet A smoke point - 1969-80 inspection data.

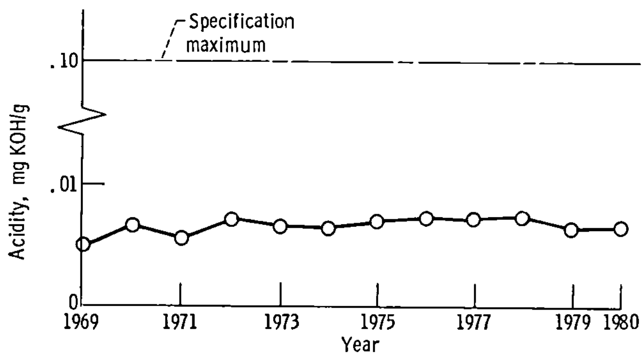


Figure 25. - Trends of median Jet A total acidity - 1969-80 inspection data.

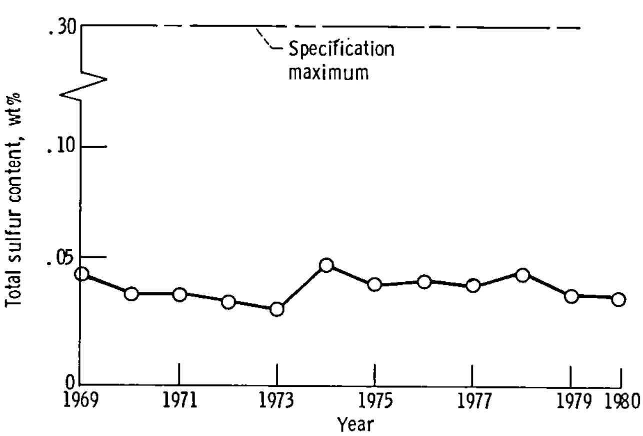


Figure 26. - Trends of median Jet A total sulfur content - 1969-80 inspection data.

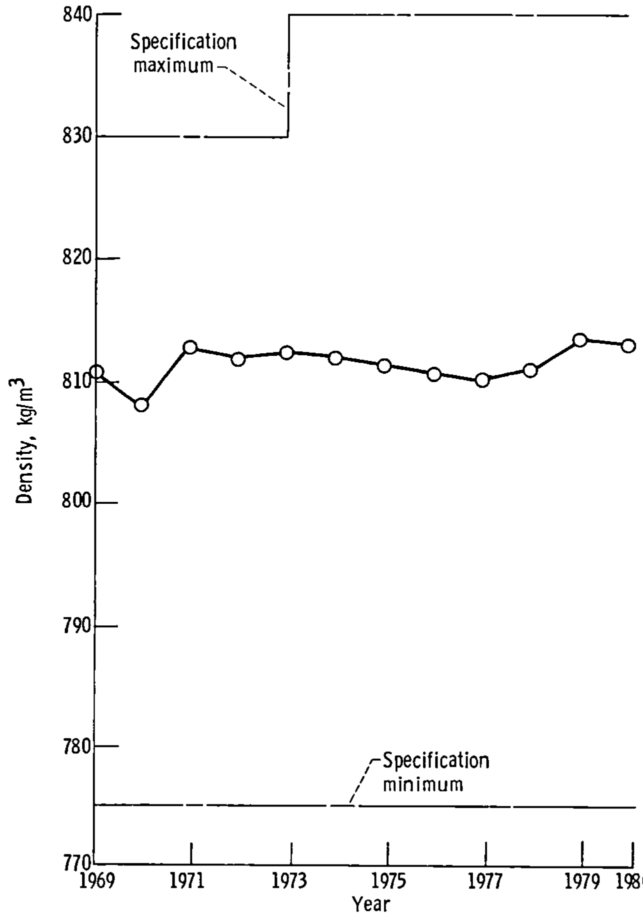


Figure 27. - Trends of median Jet A density - 1969-80 inspection data.

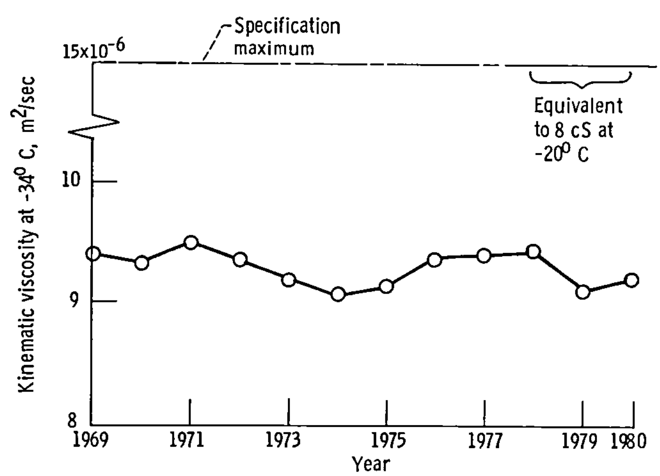


Figure 28. - Trends of median Jet A kinematic viscosity reported at -34° C - 1969-80 inspection data.

aromatics content, a "reportable" limit relaxation (footnote f, table I) provided some relief in specification-limit margins.

In summary, the plots of the median values of the selected properties as a function of time show trends, to some degree, toward the specification limits for aromatics content, mercaptan sulfur content, 10-percent distillation, and freezing point. Furthermore, the general level of the median values lies near the specification limits for aromatics content, smoke point, and freezing point.

Trends of Other Properties

The other properties with trends plotted in this report have median values well within their specification limits. With few exceptions, median values showed little change with time. Median acidity (fig. 25) and total sulfur content (fig. 26) were of the order of one-tenth their specification limits and showed no overall trends over the 12-year study period.

Median density (fig. 27) showed no overall trend, but

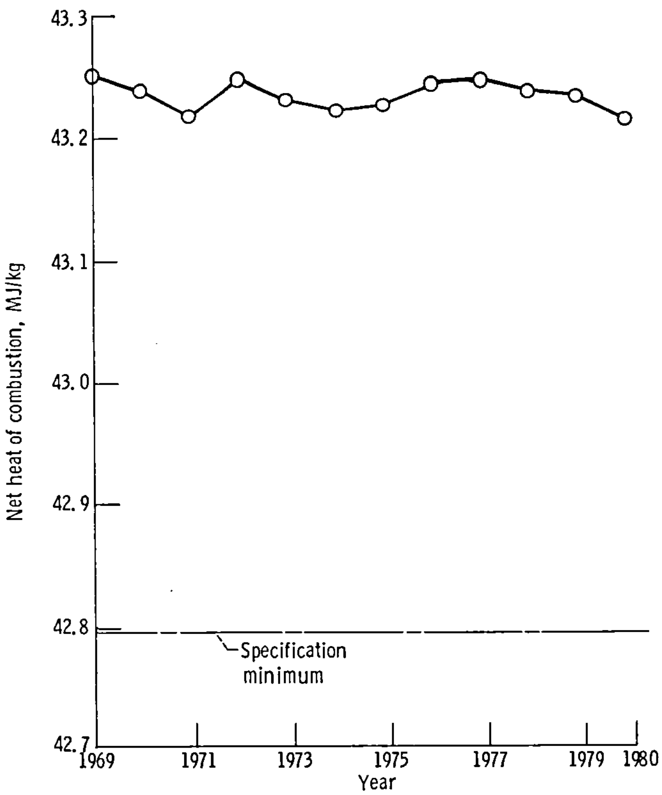


Figure 29. - Trends of median Jet A net heat of combustion - 1969-80 inspection data.

there was a slight increase in the last 4 years of the survey. The raising of the maximum specification limit for density in 1973 provided considerable margin between the median and the limit. Note that reference 12 and the petroleum industry in general report density as an API gravity, which is inversely proportional to density; hence recent trends show a decreasing API gravity. Median viscosity (fig. 28) exhibited a very small decreasing trend with time, but values were about one-half the specification limit maximum.

Median heat of combustion (fig. 29) showed a slight decrease in the last four years, but very little change overall. Although the margin between the median and the specification limit appears to be very small on a percentage basis, heat of combustion for aviation turbine

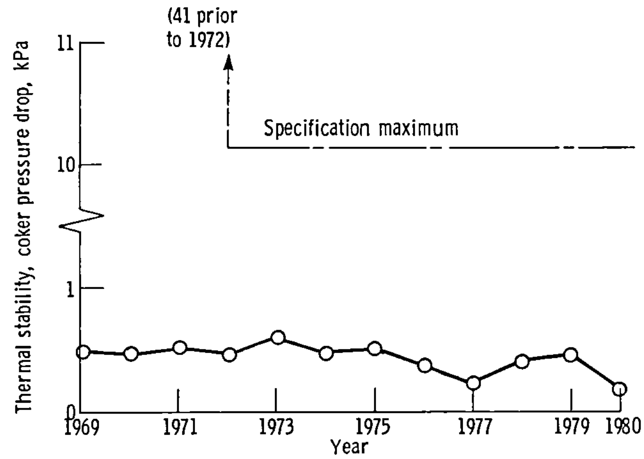


Figure 31. - Trends of median Jet A thermal stability measured by coker filter drop - 1969-80 inspection data.

fuels varied little for the complete range of possible compositions and boiling points. The entire histogram of figure 12 encompasses a range variation of only 2 percent.

Median naphthalenes content (fig. 30) also showed no overall trend except for a small increase in the last 4 years. It is of interest that the median content of naphthalenes (two-ring aromatics) in aviation turbine fuels has increased proportionately more rapidly than total aromatics content (fig. 19). Both median thermal stability (fig. 31) and existent gum (fig. 32) showed little annual variation and were at levels well below their specification limits. As noted previously, however, the central value for thermal stability, whether a mean or median, poorly represents the distribution. Improved measurement data for thermal stability could provide better information on suspected trends in the property (ref. 18).

Near-Specification Properties

Definitions

This section of the report examines aviation turbine fuel properties on the basis of their relationship to the specification limits.

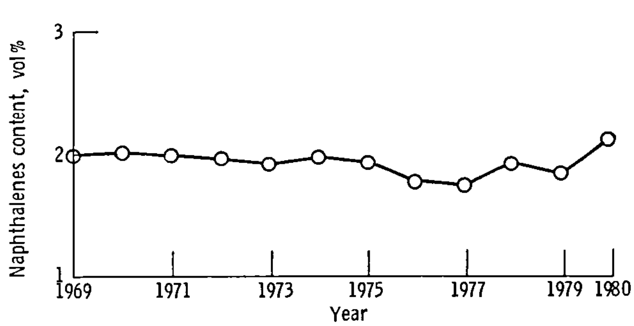


Figure 30. - Trends of median Jet A naphthalenes content - 1969-80 inspection data. (No specification limit.)

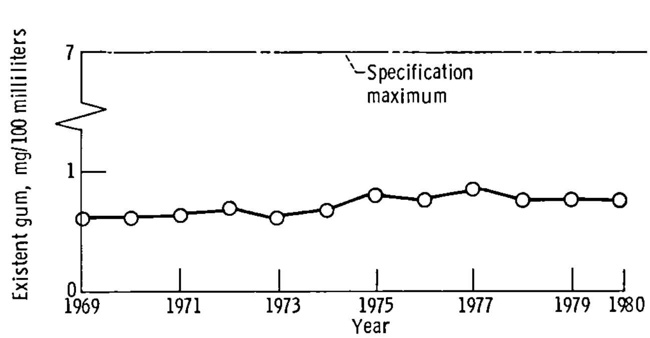


Figure 32. - Trends of median Jet A existent gum by steam evaporation at 232^{0} C - 1969-80 inspection data.

The aviation turbine fuel specification limits are absolute and are not subject to tolerances in their values (footnote A, American Society for Testing and Materials ASTM D 1655–81, ref. 15). Few properties are therefore found to be exactly at their specification limits (ref. 19), and one may suppose that fuel suppliers ordinarily apply some leeway in meeting limits to avoid off-specification measurements in acceptance reports. It is of interest, however, to examine the extent to which properties approach their specification limits by defining a range of values that may be considered near specification. In this study the near-specification range is defined by the ASTM reproducibility, ASTM Designation E 456–72 (ref. 20), which is the precision of measurements expected from tests by different observers or laboratories. Most of the ASTM test methods used for the Jet A properties include a reproducibility definition in the procedure, as determined from a survey of cooperating laboratories. By applying the reproducibility as a tolerance about the specification limit, one obtains a reasonable near-specification band of properties to be regarded as sufficiently close to their specification limit. Dickson and Karvelas (ref. 10) used the same concept for defining near-specification smoke-point observations, but they used a broader range than the ASTM reproducibility for freezing points.

Table V is a listing of the near-specification property range for the Jet A properties examined in this report. Each near-specification range was calculated by adding the reproducibility, where available, to the acceptable side of the specification limit. The few cases of over-specification properties in the inspection reports were considered near specification. Table V also shows the associated ASTM test methods. For reference the near-specification definitions in table V are shown for the current specification limits; the same reproducibility bands at different absolute levels were applied as necessary to the earlier specification limits (table IV). For certain properties (distillation residue and loss, thermal stability measurements, corrosion, and water reaction), no reproducibilities were reported. For these properties, near specification is defined as values at or beyond the specification limit. For a few of the inspection samples luminometer number was substituted for smoke point, and the survey of near-specification samples included luminometer number measurements as part of the smoke-point totals.

Survey of Near-Specification Properties

Identification of near-specification properties. – Table VI summarizes the general findings of the near-specification properties associated with the 743 inspection data samples covered in this 12-year survey. Approximately 20 percent of the samples had no near-specification properties, 30 percent had one property, 35 percent had two properties, and 13 percent had three properties near specification. Very few samples had more than three properties near specification, none more than five. Thus, as expected, most of the actual aviation turbine fuel samples had at least one property near specification, and the approach of these properties to their specification limits could be the controlling factor in fuel refining. On the other hand, despite the fact that 22 properties were defined by specification limits, it was rare that a given sample would have more than even three properties near specification.

Table VII identifies the more common near-specification properties and combinations of properties. As expected from the histograms, various combinations of aromatics content, smoke point, and freezing point dominated the near-specification properties. Since high aromatics contents are associated with poor smoke points, the frequent combination of these two near-specification properties was expected, although there were also many samples with aromatics content or smoke point alone near specification. Freezing point occurred near specification alone and also in combination with aromatics content, aromatics content and smoke point, or smoke point (rarely). The association of near-specification freezing point and aromatics content may appear contradictory, since aromatics as a class have low freezing points. Freezing points of aviation turbine fuels are quite unpredictable, however, because this property is a complex function of final boiling point and composition (general hydrocarbon types).

Table VIII is a complete summary of the Jet A properties, listing the number of samples where each property is found near specification. Separate columns show the occurrence of each near-specification property alone or in total, including combinations. The preponderance of near-specification aromatics content, freezing point, and smoke point is again evident. There were also small fractions of samples with near-specification acidity, mercaptan sulfur content, 10-percent distillation temperature, and final boiling point. In contrast, certain properties otherwise of concern in fuel handling, combustion, or performance were almost never near specification. These include total sulfur content, flashpoint, density, heat of combustion, and thermal stability.

Trends of near-specification properties. – Figure 33 shows the trends in selected near-specification properties. Annual fractions of samples with near-specification aromatics content, smoke point, freezing point, and final boiling point were plotted as data points connected for reference by line segments. The values shown are for total samples with the named property near specification, including those with combinations of other near-specification properties, corresponding to the last columns of table VIII. Hence many samples with multiple near-specification properties were duplicated in

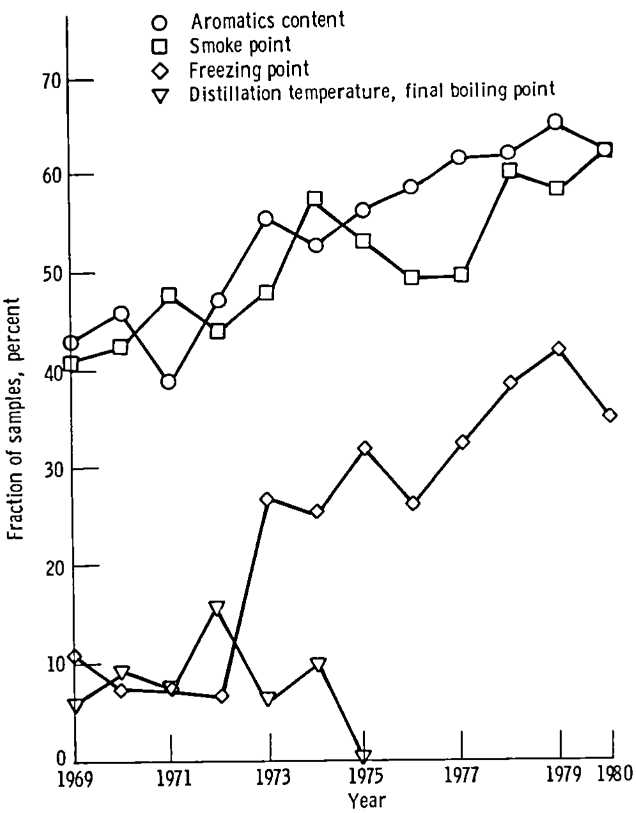


Figure 33. - Trends of probability of near-specification values for selected Jet A properties - 1969-80 inspection data.

figure 33, and total fractions add to more than 100 percent. Note that near-specification aromatics content, smoke point, and freezing point increased with time, consistent with the trends of median values (figs. 19, 24, and 18, respectively). Near-specification freezing point was low until 1973, when the specification limit was made more restrictive. In contrast, the final-boiling-point specification was made less restrictive in 1973, and no samples were found with this property near specification in later years.

Influence of near-specification definition. – Clearly, the choice of the precision band for the near-specification definition will affect the number of samples in the range. The relative spread of near-specification values for each property in table V varied considerably. Test methods for total sulfur content, density, viscosity, and heat of combustion are precise, and the near-specification range based on the ASTM reproducibility is narrow. Test methods for acidity, aromatics content, and mercaptan sulfur content, among others, are less precise, and the reproducibility band is broad. The defined near-specification band was based on currently accepted test methods and their precision, and the influence of this band width on the assessment of the relative ranking of near-specification properties was small. The properties that were almost never near specification generally showed distributions with low probabilities near the specification limit, regardless of the near-specification bandwidth. The more critical near-specification properties showed appreciable near-specification samples even with considerable adjustment of the bandwidth.

Controlling Near-Specification Properties

Another means of identifying the approach of properties to their specification limit is through the concept of a controlling near-specification property. For each inspection sample in this survey with any property near specification, one controlling near-specification property was selected. The controlling near-specification property was obviously the one property near specification for samples with a single near-specification property. For samples with combinations of near-specification properties, the controlling near-specification property was defined as the one closest to its specification limit. For a few samples with properties equally near their limits, the controlling property was arbitrarily established by choosing freezing point over smoke point and in turn smoke point over aromatics content, as applicable.

Table IX is the summary of the controlling near-specification properties. The table shows the 20 percent of samples with no properties near specification to complete the totals to 100 percent of the samples. Again, aromatics content, freezing point, and smoke point dominated the controlling near-specification properties. In fact, the only other property with any small significance was mercaptan sulfur content, controlling in about 3 percent of the samples.

Table X presents the number of samples with various controlling near-specification properties for each year of

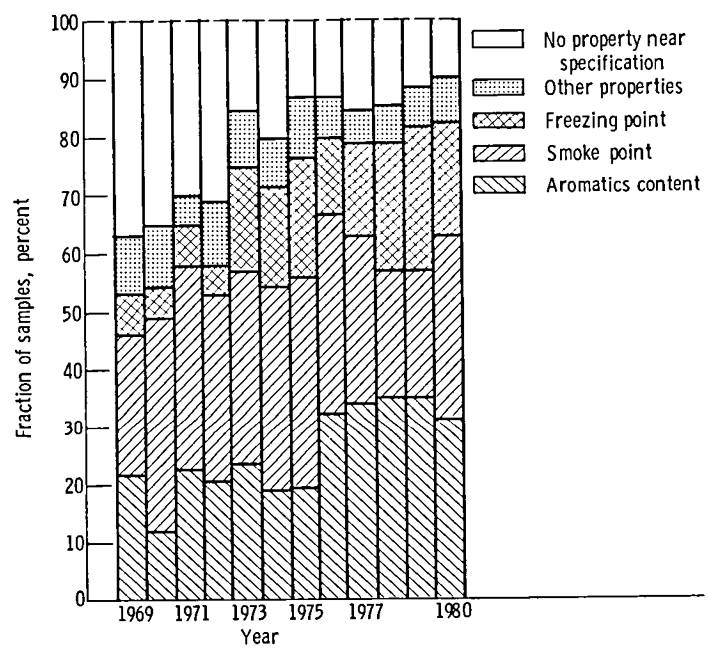


Figure 34. - Trends of apportionment of Jet A inspection data by controlling near-specification property - 1969-80 inspection data.

the inspection compilation. Figure 34 is a bar graph of the same information, showing the percentage apportionment of controlling properties for each year. Again the plot demonstrates the decreasing trend in samples with no near-specification properties. These constituted 20 percent of the overall samples, but their fraction decreased from 37 percent in 1969 to 10 percent in 1980. The sum of the controlling aromatics contents and smoke points (two properties frequently found in combination) increased from 46 percent in 1969 to around 60 percent in the last few years of the survey. Controlling freezing point was low prior to the specification change in 1973 but increased to over 20 percent in recent years.

"Reportable" Aromatics Content and Smoke Point

The definitions of near-specification aromatics content and smoke point ignore the so-called "reportable" specification-limit extensions of these properties. These extensions, explained in footnotes in table I, have, since 1974, permitted relaxation of the specification limits to a maximum of 25 percent aromatics and a minimum of 18 mm smoke point, when reported by the supplier.

Table XI illustrates the extent of samples with properties in the "reportable" range, that is, with aromatics contents and/or smoke points that would ordinarily be off specification but are permissible with the reportable extension. For each property, the table lists the annual number of samples in the reportable range and two ratios: reportable samples as a percentage of the samples with the stated property near specification and reportable samples as a percentage of all inspection samples. A third category lists the total reportable samples and their ratios for each year. The totals are less than the sum of aromatics contents and smoke points because samples with both aromatics content and smoke point reportable were not duplicated.

For several years after 1974, the fraction of fuels with reportable aromatics content was small, but the fractions increased considerably to near 20 percent of all samples in 1979 and 1980. Samples with reportable smoke points were less common, averaging about 5 percent of the total in recent years.

The near-specification property ranges of table V are based on the standard limits for aromatics content and smoke point, and all the reportable samples are included as near specification – a fair and consistent representation of the data. If the near-specification limits were shifted to apply the reproducibility band at the extended reportable specification limits, the near-specification fraction for aromatics content in 1980 would decrease from 63 percent (fig. 33) to 6 percent. The same treatment for smoke point would only decrease the near-specification smoke point from 63 percent to 22 percent because of the lesser reportable fraction.

Other Data Comparisons

Airline Delivery Data

United Airlines (UAL) maintains a data bank of inspection properties representing some 60 to 70 percent of deliveries to domestic airlines. Through the courtesy of the airline propulsion department, some of the data were furnished to the author. Summaries of the UAL data have been reported by Campbell (refs. 13 and 21). The UAL data are here compared with the DOE inspection data that constituted the survey of this report, for one annual freezing point distribution and for trends of aromatics content and smoke point.

Figure 35 shows the histograms for the 1978 DOE freezing points (60 samples) and the 1978 UAL freezing points (1774 samples) superimposed on the same grid. As is the case with the DOE data, each of the UAL fuel samples did not necessarily represent the same volume share of the total domestic refinery output, but the broad statistical sampling insured a close reflection of average fuel qualities. The DOE data are represented by broken lines enclosing a shaded area; the UAL data are represented by solid lines enclosing an open area. The much larger UAL population produced a smoother histogram, but otherwise there were only small differences between the distributions. The DOE data

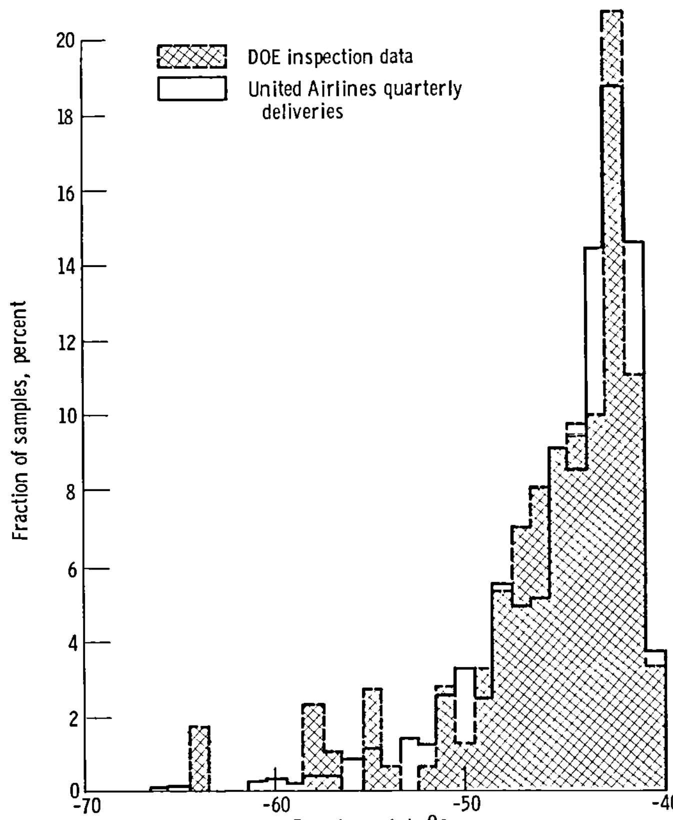


Figure 35. - Comparison of distributions of Jet A freezing point from 1978 Department of Energy and United Airlines inspection data.

have a median value of −44.0° C; the UAL data −43.4° C. Both histograms are extremely skewed.

Figure 36 plots the DOE and UAL trends for aromatics content; figure 37 plots the trends for smoke point. The DOE data are shown as yearly bar segments to 1980, and they are identical to those shown in figure 19. The UAL data are those reported in reference 21, with updating to 1979 (the latest available at this writing) from the furnished data. The UAL data are points for quarterly averages connected by line segments. The UAL averages are apparently means, and they were therefore compared with the calculated DOE means. These comparisons indicate that, for aromatics content, the UAL data show a slightly greater increase with time than the DOE data, up to a peak of 18.5 percent attained during 1978-79. For smoke points the trends are similar, but the UAL averages are up to a millimeter lower than those of the DOE data. In general, there is very good agreement between the two inspection data sets, although the larger UAL data set lies slightly closer to the specification limits for both properties.

Figure 38 compares trends of the fraction of inspection samples with reportable aromatics content and/or smoke point, that is, samples with those values within the specification-limit extensions discussed in a preceding section of this report. The DOE data are again shown as yearly bar segments, and they were plotted from the totals shown in the last row of data in table XI. The UAL data are quarterly points connected by line segments, and they are those reported in references 21 and 22 with updating to 1979 from the furnished data. The UAL data show quarterly variations that would be averaged out in the annual DOE data. The overall trends of the two data sets agree well, particularly with respect to the large relative increase in reportable samples from 1977 to 1979, although the DOE data show a higher peak in 1979.

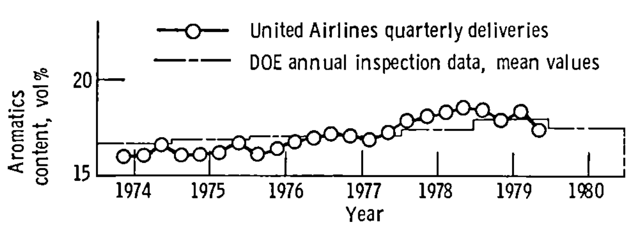


Figure 36. - Comparison of trends of average Jet A aromatics content from Department of Energy and United Airlines inspection data.

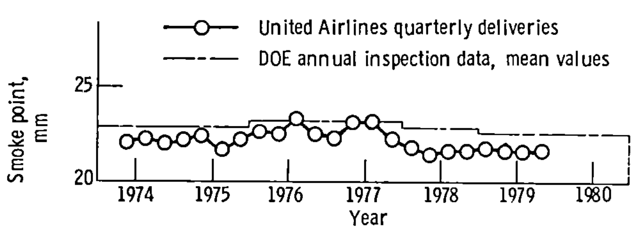


Figure 37. - Comparison of trends of average Jet A smoke point from Department of Energy and United Airlines inspection data.

Military and Premium Aviation Turbine Fuels

The examination of aviation turbine fuel properties presented in this report concentrates on those of Jet A, which is the predominant United States commercial aviation fuel. This section, however, includes a limited comparison with one nearly identical foreign fuel and two military fuels, to the extent of identifying the fraction of the Jet A samples that would meet the requirements of the other fuels.

Table XII lists the properties and specification limits of commercial Jet A-1 (as a footnote), the military fuels JP-5 and JP-8, and (for reference) Jet A. All of these fuels have similar distillation ranges. The military fuels are not to be confused with the common, wide-distillation-range fuel JP-4. JP-5 (MIL-T-5624L, ref. 23) is a Navy aviation fuel. JP-8 (MIL-T-83133A, ref. 24) is a NATO fuel, but it is certified for domestic military use. Jet A-1 is a commercial counterpart of JP-8, and it differs from Jet A only in the maximum freezing-point limit of −47° C (−50° C prior to 1980), as compared with −40° C for Jet A. Jet A-1 is no longer

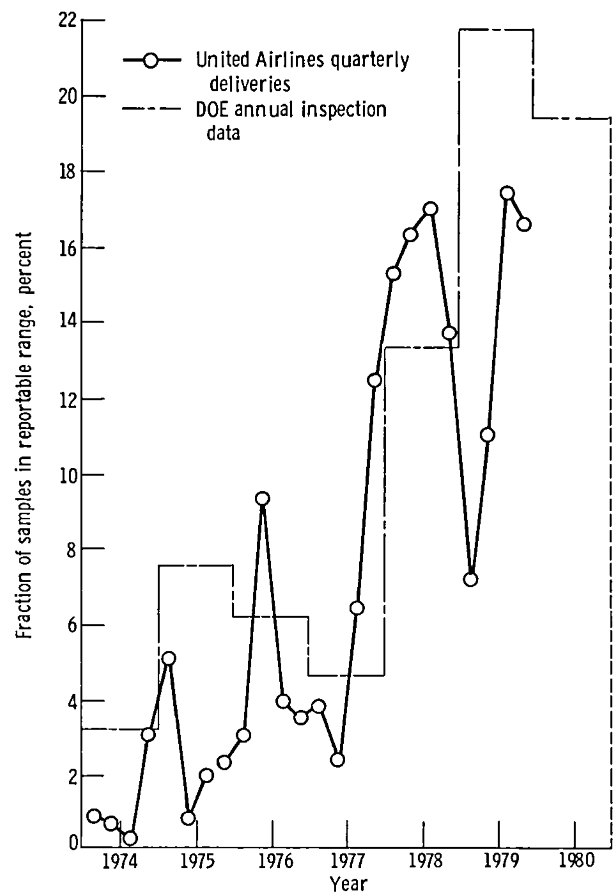


Figure 38. - Comparison of trends of samples with aromatics content and/or smoke point in the "reportable" range from Department of Energy and United Airlines inspection data.

in domestic use in the United States, but it is still supplied overseas for international service.

Table XII reveals many differences in specification limits between the military fuels and Jet A, but most are minor. The military fuel requirements include several additional properties plus alternative measurements for combustion properties and thermal stability, representing newer techniques that may eventually be adopted for commercial testing. The military fuel requirements for aromatics content and smoke point are nearly identical to the commercial fuel requirements if the reportable limit extensions are applied to the commercial specifications. Most important differences are the more restrictive military limits on acidity, mercaptan sulfur content, freezing point, and (for JP-5 only) flashpoint. These more stringent requirements may make the refining and delivery quality control of the fuels more difficult, and thus the fuels are, in a way, more premium-quality fuels than Jet A.

As an interesting exercise, the fraction of the Jet A inspection samples that would also meet the requirements of the premium fuels was calculated. All of these fuels are products with approximately the same distillation range. Hence, in a broad sense, the premium fuels represent a select portion of the Jet A product pool, and the difficulty in meeting the required quality is reflected by the fractions of the general Jet A pool they occupy. Figure 39 shows the results of this calculation. The fractions of the Jet A inspection samples with properties meeting the more stringent limits of Jet A-1 (a premium Jet A in terms of freezing point), JP-5, and JP-8 were plotted for each year of the survey. Because of many changes in specifications, military fuel data were excluded for the years prior to 1973. Jet A-1 comparisons are shown in two forms. One plot shows the fraction of samples meeting the then-existing (up to 1980) freezing-point requirement of −50° C maximum. A second plot shows, for interest, the fraction of samples meeting the present −47° C limit applied to all previous years.

The DOE inspection reports do include sample properties for fuels marketed as JP-5 and (in earlier years) Jet A-1. The comparisons in figure 39 are for the large, statistical survey of representative-quality Jet A fuels not intended for sale as premium fuels. Thus the results should not be interpreted in any quantitative sense. Nevertheless, this comparison illustrates the qualitative sensitivity of fuel availability, as implied by changes in the fraction of the random fuel samples, to more stringent property limits. Overall, about 5 percent of the Jet A samples meet the JP-5 specifications; 10 percent, the JP-8, 15 percent, the previous (−50° C freezing point) Jet A-1; and 35 percent, the present Jet A-1 specifications. The fractions are not exclusive. Some samples meet more than one of the premium fuel requirements; a few in fact meet all four. The high

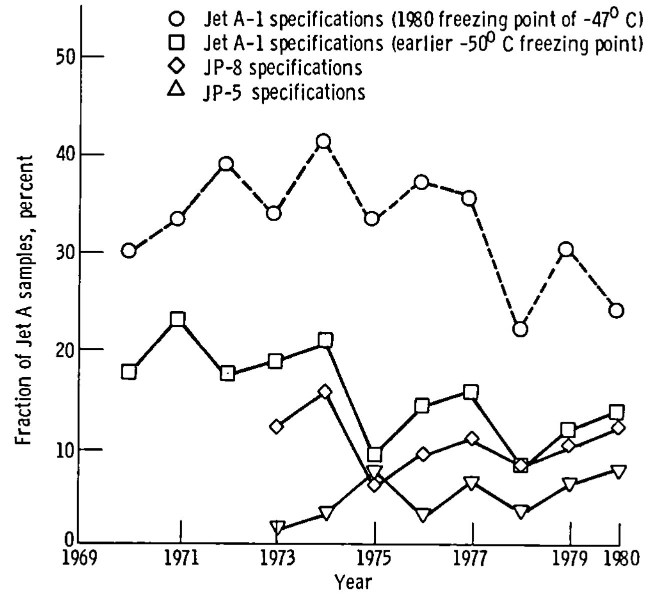


Figure 39. - Trends of Jet A inspection data samples also meeting requirements for competing premium and military fuels.

flashpoint of JP-5 appears to be the most stringent requirement in limiting the fraction of the Jet A population that will meet this additional specification. The severity of the different freezing-point requirements is illustrated by a comparison of the two Jet A types. The decreasing trend with time for the fractions meeting both Jet A-1 requirements is consistent with the increasing trend of average freezing point and the corresponding decrease in the probability of low-freezing-point samples. The two military fuel fractions show considerable annual variations but no particular trend.

Observations and calculations have been previously made to link fuel availability to property changes. As mentioned in the introduction to this report, these types of studies have the objective of examining relaxed property limits to provide an increase of fuel yield or availability. An example is the survey of Dickson and Karvelas of Bonner & Moore (ref. 10), who estimated availability increases for specification changes for two classes of fuels: wide boiling range (JP-4) and kerosine type (JP-5 and others). More recently, Peacock, et al. (ref. 25) presented studies on the same two classes of fuels that were based on calculations of yields. Lieberman and Taylor (ref. 9) also reported the influence of freezing-point and flashpoint relaxations on the availability of JP-5, on the basis of refinery-model calculations.

Discussion of Results

An interpretation of the significance of the data and trend compilations in this report depends on consideration of several economic and technological factors. Speculation on these concerns is beyond the scope of this simple examination of fuel sample properties. There are, however, certain observations of the data and their trends that are worthy of further note.

The results show that the median values of several important Jet A properties have been increasing toward their specification limits, particularly in the last few years. These properties include aromatics content, mercaptan sulfur content, 10-percent-recovered distillation temperature, freezing point, and smoke point. Of these properties, aromatics content, freezing point, and smoke point have particular significance because the distributions of property values show appreciable sample probabilities near their specification limits. In fact, these properties were near specification and very likely controlled the refining limits in over 70 percent of the inspection samples in the 12-year survey (table IX). On the other hand, other properties that are otherwise of importance in fuel handling and combustion, such as total sulfur content, flashpoint, density, heat of combustion, and thermal stability were rarely if ever near specification, and their median values varied little over the years.

The increasing trend in mean aromatics content of aviation turbine fuels in the past decade or more has been noted in previous papers (refs. 4, 6, and 13). Since modern refining of aviation turbine fuels involves little chemical conversion of the feedstocks, the increase in aromatics content reflects the increasing use of heavier, more aromatic feedstocks (note ref. 26, e.g.). A study of the aromatics content of the aviation turbine fuel distillation range for known worldwide petroleum crudes by Dukek and Longwell (ref. 2) shows very low probabilities of fuels exceeding 25 percent aromatics. This implies that the current trend of increasing aromatics content is self-limiting in the future even with a larger influx of poor-quality crudes. However, this evaluation does not take into account the effect of the future introduction of shale oil or coal-derived feedstocks nor of refining changes such as blending of converted, "cracked" stocks.

The trend in smoke points would be expected to mirror that of aromatics content. (High aromatics content implies a low smoke point.) Campbell (ref. 13) notes that, for the period 1974–77, smoke points for fuel delivered to United Airlines increased slightly, despite an increase in average aromatics contents for the same period. This trend may also be noted in the DOE data for the same period (fig. 24). However, in 1978 and succeeding years, the inspection data show a resumption of the decrease of median smoke point, which is expected as a consequence of the aromatics content increase. Smoke point, measured in millimeter increments, is a rather imprecise property for statistical calculations. Military fuel requirements include an alternative hydrogen content, a precise measurement related to a large degree directly to smoke point and inversely to aromatics content (ref. 3).

Refiners often limit the final boiling point of the product pool intended for aviation turbine fuel by the necessity of meeting the freezing-point specification. In the 12-year period of this study, there is no recognizable trend of final boiling points. Yet in the same period freezing points gradually increased from median values of around −46° C in the early years to a high of −43.3° C in 1979. Of course, compositional changes in terms of hydrocarbon group content as well as the boiling range influence freezing points. It is also possible that the overall distribution analysis conceals more subtle relationships of final-boiling-point changes and freezing-point increases. Note that the median freezing point decreased in 1980. Time will tell if this is a temporary perturbation or a longer term leveling or decrease. The unusual distribution of the freezing-point values, which makes standard statistical calculations unrepresentative, has already been noted. The skewed and double-peak distribution may be explained as a combination of two subdistributions. An appreciable fraction of samples have only aromatics content or smoke point near specification. These samples would show a range of freezing points centered at a low freezing-point value. A second grouping of samples with freezing points near specification would, by definition, have a narrow range of freezing points centered near the specification limit. It appears that these two major groups of samples are sufficiently exclusive to form the distinctive double-peak overall distribution of freezing points, but it was not possible to separate the distribution to illustrate or confirm this hypothesis.

The trend in flashpoint is unique among those of the selected, more important properties in that it is away from the minimum specification limit. In general, Jet A flashpoints are not necessarily determined by the aviation turbine fuel requirements. For economic reasons, the Jet A product is often made as a dual-purpose fuel that also conforms to the legal flashpoint (higher than 38° C in some states) for domestic kerosine. Furthermore, as pointed out by M. P. Hardy of United Airlines in a private communication, multiproduct pipeline companies impose receiving flashpoint limits of 45° C or higher to avoid off-specification flashpoints at delivery due to contamination by traces of gasoline. Figure 5 confirms that less than 4 percent of the inspection samples have flashpoints below 45° C.

The distribution and trends of aviation turbine fuel properties presented in this report show the expected results, consistent with the observations reported elsewhere. The novelty of this work lies in the extensive compilation of quantitative fuel quality data, accessible for a variety of statistical calculations. The concept of near-specification property values is very helpful in recognizing the narrowing margins between average fuel properties and their specifications, especially for aromatics content, smoke point, and freezing point. The near-specification statistics confirm the small but recognizable trends of the median values with time. The study also retrieves minimum, median, and maximum probability values for those fuel properties that are amenable to such treatment. These values can be more realistic and useful for some design and analytical studies than hypothetical specification-value fuel properties.

The projection of the selected property value trends to the future has been mentioned briefly. It is difficult to assess the effect on fuel properties of increases in aviation turbine fuel demand, shifts in competing refinery products (growth of automotive diesel, e.g.), and changes in crude feedstock properties. Some property trends are noteworthy, and these may already be a result of the response of the supplier and user requirements to the changing situation in the aviation turbine fuel market.

Summary of Results

This report is an examination of published inspection data covering 743 samples of Jet A aviation turbine fuel for the 12-year period 1969-80. The statistics in this report cover 22 properties that make up the detailed requirements of the commercial fuel specifications. Data output includes plots and tables of the distribution of property values, average and extreme values, the probability of properties approaching their specification limits, and the trends of all of these with time.

The following results were noted:

1. Fifteen of the aviation turbine fuel properties have sufficient quantitative data for summaries in the form of distribution bar graphs, or histograms. The report summarizes the characteristics of the distributions by a compilation of minimum, median, maximum, mean, and standard deviation values. Most of the distributions are conventional probability plots, but the weighting of values toward the specification limits for aromatics content, smoke point, and freezing point can be noted. The freezing-point distribution is quite unusual: there are two high-probability peaks centered at about 2° C and 8° C below the −40° C specification maximum.

2. Plots of annual average values of properties show a small but recognizable trend with time of certain properties moving toward their specification limits. These include aromatics content, mercaptan sulfur content, distillation temperature at 10 percent recovered, smoke point, and freezing point.

3. A concept of near-specification values is defined. These are the band of values about the specification limit corresponding to the American Society for Testing and Materials reproducibility precision for the method employed for the particular property. For the overall 12-year survey, about 20 percent of the samples have no near-specification properties. Most of the remaining samples have one to three near-specification properties each. Only a few samples have more than three near-specification properties; none have more than five.

4. In the most recent years of the inspection data survey, over half of the samples have near-specification values of aromatics content or smoke point. About one-third have near-specification values of freezing point. On the other hand, only a very small fraction have near-specification acidity, mercaptan sulfur content, 10-percent-recovered distillation temperature, and final boiling point. Other important properties, such as total sulfur content, flashpoint, density, heat of combustion, and thermal stability are rarely if ever near specification.

5. The fraction of samples with near-specification aromatics content or smoke point showed a marked increase with time; that with near-specification freezing point showed a moderate increase with time. The fraction of samples with no near-specification properties decreased with time, reaching 10 percent in 1980.

6. Near-specification property statistics are also reported in terms of a single controlling property for each sample and in terms of samples with "reportable" properties. The latter are those fuels with aromatics contents and/or smoke points that are off specification but within a specification extension permissible if reported by the supplier. These criteria confirm the predominance of aromatics content, smoke-point, and freezing-point values near their specification limits.

7. The statistics derived from Department of Energy inspection reports show good agreement with independent data provided by United Airlines from a large collection of company fuel deliveries.

Lewis Research Center
National Aeronautics and Space Administration,
Cleveland, Ohio, March 29, 1982

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TABLE I. - AVIATION TURBINE FUEL SPECIFICATIONS AND INSPECTION DATA

Property	Specification limit, ASTM D 1655-81, Jet A	Inspection data (ref. 12)
Acidity, mg KOH/g	0.1 max.	Yes
Aromatics, vol%	[a]20 max.	↓
Sulfur, mercaptan, wt%	0.003 max.	↓
Sulfur, total, wt%	0.3 max.	↓
Distillation temperature, 10 percent recovered, °C	204 max.	Yes[b]
Distillation temperature, final boiling point, °C	300 max.	Yes[b]
Distillation residue, vol%	1.5 max.	Yes
Distillation loss, vol%	1.5 max.	Yes
Flashpoint, °C	38 min.	Yes[b]
Density at 15° C, kg/m^3	775 min.	Yes[c]
	840 max.	
Freezing point, °C	-40 max.	Yes[b]
Viscosity at -20° C, m^2/sec	8×10^{-6} max.	Yes[d]
Net heat of combustion, MJ/kg	42.8 min.	Yes[e]
Alternative combustion properties:		
Smoke point (naphthalenes $\leq$ 3 vol%), mm	[f]20 min.	Yes
Smoke point (naphthalenes > 3 vol%), mm	25 min.	Yes[g]
Luminometer number	45 min.	Yes[h]
Corrosion, copper strip tarnish number	No. 1 max.	Yes
Thermal stability, coker pressure drop[i], kPa	10 max.	Yes[j]
Thermal stability, coker preheater deposit	Code 3 max.	Yes
Existent gum, mg/100 milliliters	7 max.	↓
Water reaction, separation rating	No. 2 max.	↓
Water reaction, interface rating[k]	No. 1b max.	↓

[a]Aromatics content over 20 vol% but not exceeding 25 vol% is permitted provided supplier notifies purchaser within 90 days of shipment.

[b]Inspection data were reported in degrees Fahrenheit.

[c]Inspection data were reported in degrees API gravity. (Equivalent limits are 51° API, minimum density, to 37° API, maximum density.)

[d]Inspection data were reported in centistokes at -34° C. (Limit of 8 cS at -20° C is nominally equivalent to 15 cS at -34° C.)

[e]Inspection data were reported in Btu per pound.

[f]Smoke points below 20 but not less than 18, with a maximum of 3 vol% naphthalenes, are permitted provided supplier notifies purchaser within 90 days of shipment.

[g]Inspection data were reported for both smoke points and naphthalenes for all samples.

[h]Luminometer number was reported as alternative for only a small fraction of the samples.

[i]Specification included an alternative jet fuel thermal oxidation tester method, but this was not reported in inspection data.

[j]Inspection data were reported in pounds per square inch.

[k]Interface rating was reported as alternative for only a small fraction of samples.

TABLE II. - SUMMARY OF AVIATION TURBINE FUEL PROPERTIES - COMBINED 1969-80 INSPECTION DATA

Property	Number of samples	Mean	Standard deviation	Percentiles		
				5	50 (median)	95
Acidity, mg KOH/g	706	0.0098	0.0144	0	0.0065	0.030
Aromatics, vol%	737	16.8	2.59	12.5	17.2	20.5
Sulfur, mercaptan, wt%	659	0.00072	0.00080	0.00002	0.00046	0.0020
Sulfur, total, wt%	740	0.052	0.048	0.006	0.040	0.14
Distillation temperature, 10 percent recovered, °C	743	188.3	7.52	176.1	188.6	199.3
Final boiling point, °C	743	267.2	9.40	252.8	268.1	281.4
Flashpoint, °C	741	53.9	5.29	45.6	53.3	63.3
Density at 15° C, kg/m^3	743	811.3	7.51	799.5	811.5	823.8
Freezing point, °C	742	-45.7	4.37	-53.9	-44.7	-40.5
Viscosity at -34° C, m^2/sec	695	9.20×10^{-6}	1.88×10^{-6}	5.89×10^{-6}	9.29×10^{-6}	12.3×10^{-6}
Net heat of combustion, MJ/kg	707	43.228	0.1059	43.055	43.235	43.369
Smoke point, mm	699	23.0	2.21	19.8	22.9	26.5
Naphthalenes, vol%	577	1.80	0.728	0.35	1.95	2.78
Thermal stability, coker pressure drop, kPa	722	0.96	1.7	0	0.47	3.9
Existent gum, mg/100 milliliters	681	0.82	0.68	0	0.69	2.1

TABLE III. - SUMMARY OF AVIATION TURBINE FUEL PROPERTIES - 1980 INSPECTION DATA

Property	Number of samples	Mean	Standard deviation	Percentiles		
				5	50 (median)	95
Acidity, mg KOH/g	63	0.0111	0.0165	0	0.0062	0.034
Aromatics, vol%	66	17.5	2.70	14.0	17.7	21.0
Sulfur, mercaptan, wt%	58	0.00079	0.00061	0.00005	0.00069	0.0021
Sulfur, total, wt%	60	0.052	0.051	0	0.037	0.14
Distillation temperature, 10 percent recovered, °C	67	190.4	7.69	177.1	192.1	201.4
Final boiling point, °C	67	268.0	9.04	252.2	268.8	281.3
Flashpoint, °C	65	55.2	5.93	46.4	54.6	64.1
Density at 15° C, kg/m^3	67	812.9	7.36	800.8	812.8	824.0
Freezing point, °C	67	-45.2	4.73	-55.6	-44.3	-40.3
Viscosity at -34° C, m^2/sec	53	8.78×10^{-6}	2.45×10^{-6}	4.28×10^{-6}	9.20×10^{-6}	12.8×10^{-6}
Net heat of combustion, MJ/kg	57	43.203	0.0969	43.027	43.210	43.343
Smoke point, mm	64	22.5	2.29	19.5	21.9	26.3
Naphthalenes, vol%	50	1.97	0.761	0.23	2.11	2.89
Thermal stability, coker pressure drop, kPa	64	0.71	1.20	0	0.19	3.4
Existent gum, mg/100 milliliters	63	0.92	0.69	0	0.74	2.2

TABLE IV. - CHANGES IN JET A SPECIFICATION LIMITS, 1969-80

Property	Original specification limit	Later specification limit	Date of change
Aromatics, vol%	20 max.	[a]25 max.	1974
Distillation temperature, 50 percent recovered, °C	232 max.	Dropped[b]	1975
Distillation temperature, final boiling point, °C	288 max.	300 max.	1975
Flashpoint, °C	40.6 min.	37.8 min.	1975
	65.6 max.	Dropped	1973
Density at 15° C, kg/m^3	[c]830 max.	[c]840 max.	1973
Freezing point, °C	-38 max.	-40 max.	1973
Viscosity at -34° C, m^2/sec	15×10^{-6} max.	-----------	----
Viscosity at -20° C, m^2/sec	------------	8×10^{-6} max.	1978
Smoke point (naphthalenes, 3 vol%), mm	20 min.	18[a] min.	1974
Thermal stability, coker pressure drop[d], kPa	41 max.	10 max.	1972

[a]Extended limits require notification of purchaser by supplier.
[b]50 Percent distillation temperature must be reported, although limit was dropped.
[c]Equivalent change from 39° to 37° API gravity.
[d]Alternative procedure for jet fuel thermal oxidation tester introduced in 1975.

TABLE V. - DEFINITION OF NEAR-SPECIFICATION PROPERTIES

Property	ASTM test method[a]	Reproducibility	Near-specification property range
Acidity, mg KOH/g	D 974	0.04	0.06 to 0.10
Aromatics, vol%	D 1319	3.2	16.8 to 20
Sulfur, mercaptan, wt%	D 1323[b]	0.0006	0.0024 to 0.003
Sulfur, total, wt%	D 1266	0.0175	0.283 to 0.3
Distillation temperature, 10 percent recovered, °C	D 86	4.4	200 to 204
Distillation, final boiling point, °C	D 86	10.5	290 to 300
Distillation residue, vol%	D 86	None	1.5
Distillation loss, vol%	D 86	None	1.5
Flashpoint, °C	D 56	2.2	40.0 to 37.8
Density at 15° C, kg/m^3	D 1298	[c]1.4	776.3 to 775 838.5 to 840
Freezing point, °C	D 2386	2.6	-42.6 to -40
Viscosity at -34° C, m^2/sec	D 445	[d]0.11×10^{-6}	14.89×10^{-6} to 15×10^{-6}
Net heat of combustion, MJ/kg	D 1405	0.035	42.84 to 42.80
Smoke point, mm	D 1322	3	23 to 20
Naphthalenes, vol%	D 1840	0.11	2.89 to 3.0
Luminometer number	D 1740	8.8	53.8 to 45
Corrosion, copper strip tarnish number	D 130	None	No. 1
Thermal stability, coker pressure drop, kPa	D 1660	None[f]	10
Thermal stability, coker deposit code	D 1660	None[f]	Code 3
Existent gum, mg/100 milliliters	D 381	[e]3.5	3.5 to 7
Water reaction, separation rating	D 1094	None	No. 2
Water reaction, interface rating	D 1094	None	No. 1b

[a]Test methods prescribed by ASTM D 1655-81, Jet A (ref. 15). Where there are choices or alternatives, methods shown are those cited for the inspection data (ref. 12).
[b]ASTM D 1655-81 requires method D 3227, but earlier specifications and all inspection data use D 1323.
[c]Approximate conversion from 0.3° API gravity.
[d]Obsolete viscosity temperature used to correspond to inspection data. Reproducibility estimated as 0.7 percent from ASTM method.
[e]Estimate from graph in ASTM method.
[f]Reproducibility limits stated in ASTM method, but they are wide and uncertain.

TABLE VI. - NEAR-SPECIFICATION PROPERTIES, 1969-80

INSPECTION DATA - SUMMARY BY NUMBER OF

PROPERTIES PER SAMPLE

Samples with-	Number	Fraction of samples, percent
No properties near specification	151	20.3
One property near specification	220	29.6
Two properties near specification	264	35.5
Three properties near specification	97	13.1
Four properties near specification	10	1.4
Five properties near specification	1	0.1
	743	100.0

TABLE VII. - NEAR-SPECIFICATION PROPERTIES, 1969-80 INSPECTION

DATA - IDENTIFICATION OF MOST COMMON PROPERTY COMBINATIONS

	Number of samples	Fraction of samples, percent
No properties near specification	151	20.3
Aromatics and smoke point[a] near specification	172	23.2
Smoke point[a] only near specification	82	11.0
Aromatics only near specification	73	9.8
Freezing point, aromatics, and smoke point[a] near specification	52	7.0
Freezing point only near specification	42	5.7
Freezing point and aromatics near specification	40	5.4
Freezing point and smoke point[a] near specification	18	2.4
Final boiling point only near specification	10	1.3
Aromatics, smoke point[a], and 10-percent distillation near specification	10	1.3
Aromatics, smoke point[a], and final boiling point near specification	7	1.0
All other combinations	86	11.6
	743	100.0

[a]Smoke point near specification includes samples with any of the alternative combustion properties near specification: smoke point, smoke point plus naphthalenes, or luminometer number.

TABLE VIII. - NEAR-SPECIFICATION PROPERTIES, 1969-80 INSPECTION DATA - SUMMARY BY PROPERTY

Property	Samples with only listed property near specification		Total samples with listed property near specification, including combinations with other near-specification properties	
	Number	Fraction of total, percent	Number	Fraction of total, percent
Acidity	1	0.1	13	1.7
Aromatics	73	9.8	401	54.0
Sulfur, mercaptan	5	.7	23	3.1
Sulfur, total	0	0	0	0
Distillation temperature, 10 percent recovered	5	.7	27	3.6
Distillation temperature, final boiling point	10	1.3	32	4.3
Distillation residue	1	.1	2	.3
Distillation loss	0	0	0	0
Flashpoint	1	.1	7	.9
Density (min.)	0	0	0	0
Density (max.)	0	0	3	.4
Freezing point	42	5.7	182	24.5
Viscosity	0	0	1	.1
Net heat of combustion	0	0	0	0
Smoke point[a]	82	11.0	380	51.1
Corrosion	0	0	0	0
Thermal stability, coker pressure drop	↓	↓	4	.5
Thermal stability, coker preheater deposit code	↓	↓	1	.1
Existent gum	↓	↓	6	.8
Water reaction:				
Separation rating	↓	↓	2	.3
Interface rating	↓	↓	0	0

[a]Smoke point near specification includes samples with any of the alternative combustion properties near specification: smoke point, smoke point plus naphthalenes, or luminometer number.

TABLE IX. - CONTROLLING NEAR-SPECIFICATION PROPERTIES - 1969-80 INSPECTION DATA

	Samples where property is controlling	
	Number	Fraction of total, percent
Acidity	9	1.2
Aromatics	191	25.7
Sulfur, mercaptan	21	2.8
Distillation temperature, 10 percent recovered	8	1.1
Distillation temperature, final boiling point	10	1.4
Distillation residue	1	0.1
Flashpoint	3	0.4
Density (maximum)	1	0.1
Freezing point	112	15.2
Viscosity	0	0
Smoke point[a]	231	31.1
Thermal stability, coker pressure drop	4	0.5
Thermal, coker preheater deposit code	0	0
Existent gum	1	0.1
Water reaction, separation rating	0	0
No property near specification	151	20.3
Total	743	100.0

[a]Smoke point includes the sum of the alternatives: smoke point, smoke point plus naphthalenes, and luminometer number.

TABLE X. - TRENDS IN CONTROLLING NEAR-SPECIFICATION PROPERTIES

Controlling near-specification property	Number of samples per year											
	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Acidity	2	2	0	2	0	1	0	0	0	0	1	1
Aromatics	12	7	13	13	15	12	13	21	22	21	21	21
Sulfur, mercaptan	2	0	1	1	1	3	3	2	3	1	2	2
Distillation temperature, 10 percent recovered	0	1	0	0	2	0	1	1	0	1	1	1
Distillation temperature, final boiling point	0	2	2	4	1	1	0	0	0	0	0	0
Freezing point	4	3	4	3	12	11	14	9	10	13	15	14
Smoke point[a]	13	21	20	21	22	22	24	22	19	13	13	21
Other properties[b]	1	1	0	0	2	0	2	1	1	2	0	0
No near-specification property	20	20	17	20	10	13	9	9	10	9	7	7

[a]Smoke point includes the sum of the alternatives: smoke point, smoke point plus naphthalenes, and luminometer number.
[b]Other controlling near-specification properties are thermal stability (coker pressure drop), 4 samples; flashpoint, 3 samples; distillation residue, density (high), and existent gum, 1 sample each.

TABLE XI. - TRENDS OF SAMPLES IN "REPORTABLE" RANGE

Property	Year						
	1974	1975	1976	1977	1978	1979	1980
Aromatics:							
Number of samples in "reportable" range	2	4	4	3	5	12	11
Ratio of "reportable" to near specification, percent	6.1	10.8	10.5	7.5	13.5	30.8	26.2
Ratio of "reportable" to all samples, percent	3.2	6.1	6.2	4.6	8.3	20.0	16.4
Smoke point:							
Number of samples in "reportable" range	0	1	1	0	4	3	3
Ratio of "reportable" to near specification, percent	0	2.9	3.1	0	11.1	8.6	7.1
Ratio of "reportable" to all samples, percent	0	1.5	1.5	0	6.7	5.0	4.5
Total samples in "reportable" range	2	5	4	3	8	13	13
Ratio of above to near specification, percent	4.5	10.0	8.3	6.3	17.8	27.7	24.5
Ratio of above to all samples, percent	3.2	7.6	6.2	4.6	13.3	21.7	19.4

TABLE XII. - COMPARISON OF AVIATION TURBINE FUEL MILITARY AND COMMERCIAL SPECIFICATIONS

Property	Specification limits		
	Commercial Jet A	Military	
		JP-5	JP-8
Acidity, mg KOH/g	0.1 max.	0.015	0.015
Aromatics, vol%	[a]20 max.	25	25
Olefins, vol%	(b)	5.0 max.	5.0
Sulfur, mercaptan, wt%	0.003 max.	0.001	0.001
Sulfur, total, wt%	0.3 max.	0.4	0.3
Distillation temperature, 10 percent recovered, °C	204 max.	205	205
Distillation temperature, final boiling point, °C	300 max.	290	300
Distillation residue, vol%	1.5 max.	1.5	1.5
Distillation loss, vol%	1.5 max.	1.5	1.5
Explosiveness, percent	(b)	50 max.	(b)
Flashpoint, °C	38 min.	60	38
Density at 15° C, kg/m^3	775 min.	788	775
	840 max.	845	840
Freezing point, °C	[c]-40 max.	-46	-50
Viscosity at -20° C, m^2/sec	8×10^{-6} max.	8.5×10^{-6}	8×10^{-6}
Net heat of combustion, MJ/kg	42.8 min.	42.6	42.8
Alternative combustion properties:			
Hydrogen content, wt%	(b)	13.5 min.	13.5
Smoke point (naphthalenes >3 vol%), mm	[d]20 min.	(b)	(b)
Smoke point (no naphthalene restriction), mm	25 min.	19	19
Luminometer number	45 min.	(b)	(b)
Corrosion, copper strip tarnish number	No. 1 max.	No. 1b	No. 1b
Alternative thermal stability requirements:			
Coker pressure drop, kPa	10 max.	(b)	(b)
Coker preheater deposit code	Code 3 max.	(b)	(b)
JFTOT[e] pressure drop, kPa	3.3 max.	3.3	3.3
JFTOT tube deposit code	Code 3 max.	Code 3	Code 3
Existent gum, mg/100 milliliters	7 max.	7	7
Particulate matter, mg/liter	(b)	1.0 max.	1.0
Water reaction, separation rating	No. 2 max.	(b)	(b)
Water reaction, interface rating	No. 1b max.	No. 1b	No. 1b
Water separation index, modified	(b)	85 min.	[f]85
Additives	(g)	(h)	(h)
Electrical conductivity, pS/m	(i)	200-600	200-600

[a]Aromatics up to 25 percent permitted when reported by supplier.
[b]No specification.
[c]Jet A-1 differs from Jet A only in maximum freezing-point specification of -47° C (-50° C prior to 1980).
[d]Smoke points to 18 are permitted when reported by supplier.
[e]Jet fuel thermal oxidation tester.
[f]Lower limits permitted when certain additives are used.
[g]Additives permitted, but not required.
[h]Antioxidant, corrosion inhibitor, icing inhibitor, and electrical conductivity additives required.
[i]Electrical conductivity limits of 50 to 450 apply only where electrical conductivity additive is used.

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15. Supplementary Notes

16. Abstract

Plots and tables, compiled from Department of Energy (and predecessor agency) inspection reports from 1969 to 1980, present ranges, averages, extremes, and trends for most of the 22 properties of Jet A aviation turbine fuel. In recent years, average values of aromatics content, mercaptan sulfur content, distillation temperature at 10 percent recovered, smoke point, and freezing point show small but recognizable trends toward their specification limits. About 80 percent of the fuel samples had at least one property near specification, defined as within a standard band about the specification limit. By far the most common near-specification properties were aromatics content, smoke point, and freezing point.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Aviation fuel; Turbine fuel; Hydrocarbon fuel; Fuel aromatics content; Smoke point; Fuel freezing point	Unclassified - unlimited STAR Category 28

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