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THERMAL STABILITY OF SOME AIRCRAFT TURBINE FUELS DERIVED FROM OIL SHALE AND COAL

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SUMMARY

Thermal stability breakpoint temperatures are shown for 32 jet fuels prepared from oil-shale and coal-syncrudes by various degrees of hydrogenation. Low severity hydrotreated shale oils, with nitrogen contents of 0.1 to 0.24 weight percent, had breakpoint temperatures in the 477 to 505 K (400° to 450° F) range. Higher severity treatment, lowering nitrogen levels to 0.008 to 0.017 weight percent, resulted in breakpoint temperatures in the 505 to 533 K (450° to 500° F) range.

Coal-derived fuels showed generally increasing breakpoint temperatures with increasing weight percent hydrogen, fuels below 13 weight percent hydrogen having breakpoints below 533 K (500° F).

Comparisons are shown with similar literature data.

INTRODUCTION

This report presents thermal stability breakpoint temperatures data on a series of aircraft turbine type fuels prepared from oil shale and coal syncrudes.

Little information exists in the literature on the general properties and characteristics of fuels derived from synthetic crude oils. The Lewis Research Center of NASA is engaged in a program to study the possible impacts of obtaining and using aircraft turbine type fuels derived from oil shale and coal syncrudes. As part of this program a series of such fuels was prepared from TOSCO, H-Coal and COED syncrudes by the Atlantic-Richfield Company (ARCO) under a contract with NASA (ref. 1). The purpose of this ARCO preparation contract was to determine the processing steps and conditions necessary to meet certain yield and specification requirements for the final product fuels. The ARCO contract was to determine the processing conditions and the product quality at two yields (about 20 and 40 percent) and at two levels of hydrogenation severity for each yield, of TOSCO shale oil and for two levels of hydrogenation severity for the H-Coal and COED coal syncrudes. The yields from the TOSCO syncrude were varied by using hydrocracking to attain the higher yield. The two levels of hydrogenation severity for all three syncrudes were obtained by varying the pressures (10.3×10^6 to 17.2×10^6 N/m^2, or 1500 to 2500 psi), temperatures (607 to 675 K or 634^o to 755^o F), and weight hourly space velocities (0.36 to 1.5). Each process stream was further split by distillation to give four distillation ranges. The product specifications that were required to be met were the levels of hydrogen, nitrogen, and sulfur content. All the physical and chemical tests required for aircraft turbine fuels were reported by ARCO for the 32 fuels.

Thermal stability data for such fuels are especially scarce. The evaluation of the thermal stability of a fuel should reveal any tendency of that fuel toward instabilities which could affect its performance in an aircraft fuel system. For example, there could be the tendency toward gum or deposit formation on heated surfaces or the tendency to form particulates which might plug small passageways in the fuel system.

The purpose of the work presented herein was to determine the thermal stability breakpoint temperatures on the fuels prepared by ARCO and to see if any correlations of breakpoint temperatures with fuel properties or processing would be evident. The breakpoint temperature data determined at NASA are compared with the single temperature (260^o C) determinations made by ARCO on these same fuels.

The data cover 32 fuels. Sixteen of these fuels were from a TOSCO shale oil syncrude, 8 from an H-Coal syncrude, and 8 from a COED (coal-derived) syncrude. The breakpoint temperature range investigated was 477 to 589 K (400^o to 600^o F).

EXPERIMENTAL PROCEDURE

Apparatus

The thermal stability data were obtained using the Alcor jet fuel thermal oxidation tester (JFTOT) apparatus and procedure which are described in detail in ASTM D 3241 (ref. 2). A cross-sectional sketch of the test section is shown in figure 1.

Filtered, aerated fuel flows upward through an annulus formed between an outer housing and an inner heated tube and then out through a test filter. The aluminum heater tube is heated electrically. Figure 2 shows a typical longitudinal temperature profile which was obtained by a traversing thermocouple located inside the heater tube. The maximum temperature, at a position index of 39 (39 mm from the fuel inlet position), is the temperature recorded as the JFTOT temperature. Some measurements and calculated values of flow velocity and residence time relating to the test section are also noted in figure 1. At the design flow rate of 3 cubic centimeters per minute the flow velocity through the annulus is about 0.5 centimeter per second and the residence time in the annulus is approximately 12 seconds.

The fuel is pressurized with nitrogen (N_2) to 3.4×10^6 newtons per square meter (500 psig) to prevent fuel vaporization at the test temperature (ref. 3). The test lasts for $2\frac{1}{2}$ hours and requires at least 450 cubic centimeters of fuel for a test run.

Two types of fuel instabilities that may affect performance of a jet fuel in an aircraft fuel system are expected to be in evidence in this type of test. First, the tendency to form gum or deposits on heat exchanger tubes or other heated surfaces would show up as deposits on the test heater surface; second, the tendency of the fuel to form particulates which might clog fuel orifices or filters would show up as an increasing pressure drop with time across the test filter.

The test filter pressure drop is recorded during the test procedure. The heater tube deposit is checked at the end of the run. The tube deposit can be rated visually (by comparison with a color standard) and given a numerical rating of 0 (clean tube) to 4 (heavy deposit) or it can be rated with an Alcor Mark 8A tube deposit rater (TDR). All the tube deposits cited in this report have been made with the TDR.

The TDR is a light reflectance measurement device in which the heater tube can be spun on its axis to give an average circumferential reading. While the tube is being spun, it can be scanned axially. The TDR scale is so calibrated that a zero reading indicates a clean tube and a 50 reading (the maximum) indicates a very heavy deposit.

For the results reported herein, it has arbitrarily been assumed that a maximum TDR spun rating of 13 or below is a pass condition for the test. Some rationale for using this value can be noted from figure 3 (ref. 4), which indicates that a TDR spun rating of 13 would have received a visual pass rating of 2 or less on all the tests used for this particular comparison. Since the value of 13 is also in agreement with the pass value used by Exxon Research and Engineering (ref. 5), the results of both sets of experiments are more readily comparable.

The standard procedure in ASTM D 3241 calls for a test at 533 K (500° F). If the fuel does not pass the stability criteria at this temperature, a second test at 519 K (475° F) is made, and the results at both temperatures are reported. In the tests herein it was attempted to select test temperatures that would bracket the spun TDR value of 13 and to label the temperature at which a maximum value of 13 was indicated as the "break point temperature". Where the break point temperature was indicated to be above the highest temperature used, it was simply labelled "above T". No runs were made above 589 K (600° F).

Fuels

The fuels used in this study were prepared under a contract study by Atlantic Richfield Company (ARCO). The details of preparation and properties of the finished samples are reported in reference 1. The preparations are now described briefly.

The flow system schematics of figures 4(a) to (c) show the principal details of the processing that was carried out on the three syncrudes. It can be noted in figure 4(a) that the low yield TOSCO samples were obtained by hydrotreating only the 361 to 616 K (190^{o} to 650^{o} F) cut from the crude. The high yield samples, however, also contain material from the 616 to 783 K (650^{o} to 950^{o} F) cut of the crude which has been hydrocracked. The H-Coal samples (fig. 4(b)) received only a single stage hydrotreatment but at more severe conditions than the comparable range for TOSCO processing. The COED samples (fig. 4(c)) contain hydrotreated IBP to 561 K (IBP to 550^{o} F) crude material and hydrocracked 561 to 700 K (550^{o} to 800^{o} F) crude products, similar to the high-yield TOSCO samples.

Each of the streams labelled "Final sample blends" in figure 4 actually consisted of two separate hydrotreatment severity runs. And, each of these separate run streams was fractionated into the group of four different boiling range final products.

The properties of the final sample blends as determined by ARCO (ref. 6) are shown in table I. It should be emphasized that the objective in processing these fuels was not to produce finished fuels that would necessarily meet all aircraft turbine fuel specifications. Rather, the objective was to meet (1) the yield, (2) the processing severity to meet the H, N, and S levels, and (3) the boiling point range conditions. The full range of aircraft turbine fuel specification tests was then carried out on these blends.

A recently completed similar study by Exxon Research and Engineering (ref. 5) produced a series of aircraft turbine fuels of the JP-4 and Jet A type from five syncrudes: Paraho, TOSCO, and Garrett shale syncrudes and H-Coal and Synthoil coal syncrudes. In this study, also, the effect of varying the severity of processing on the final product properties was investigated. The flow system schematics of figures 5(a) to (3) show the principal details of the processing that was carried out on these five syncrudes. The thermal stability data (JFTOT) obtained by Exxon on these fuels and included in reference 5 will be used in some of the later comparisons of results.

RESULTS AND DISCUSSION

The spun TDR values measured on the 32 ARCO samples are shown in figure 6. The ARCO fuel sample designations are used on the figures for identification. Scans were made from tube position index values of 20 through 54 (see fig. 2).

The TOSCO shale sample TDR values show a general symmetry around the maximum axial temperature location (position index, 39) as do the low-severity H-Coal spun TDR values. The high-severity H-Coal TDR values are comparatively more random; however, they are also all fairly low (max. value shown is ≤ 7.0). Most of the COED sample TDR values show no axial symmetry either. No significance is attached to this observation at the present time, it is simply noted.

The maximum values of spun TDR are plotted against test temperature in figure 7. In most cases no pressure drop buildup across the test filter was observed during the $2\frac{1}{2}$-hour runs. In those few cases where filter ΔP buildup did occur, the data are shown in figure 8. In only one case, with fuel number 33430, did the fuel fail to pass the ΔP test while still not showing much tube deposit.

The breakpoint temperatures, defined as the temperatures at which a maximum spun TDR value of 13 is expected, were determined from the plots of figure 7 (where maximum spun TDR was the criterion), or they were estimated from figure 8 where ΔP was the criterion (i.e., where ΔP exceeds 25 mm Hg before the end of the test).

These breakpoint temperature data are summarized in table II along with some of the fuel properties for which comparisons are subsequently made. Also shown in this table are the visual tube ratings taken by ARCO of JFTOT tests on these same materials at 533 K (500° F). A similar table made from the Exxon data (ref. 5) is presented herein as table III for comparison purposes.

A comparison of the breakpoint temperature data taken at Lewis with the visual ratings obtained on the same sample materials at ARCO is shown in figure 9. In the visual rating method, a value of less than 3 at a test temperature of 533 K (500° F) is required for a pass condition. It can be seen that for all but four fuels the pass or fail criterion was in agreement by either rating procedure. Three of the four not in agreement were very close, probably within the range of repeatability of the tests. Only one fuel sample seemed to be in marked disagreement, sample 33318. This is a high nitrogen content fuel, and the visual rating reported seems to be out of line with the other samples in the TOSCO low yield - low severity treatment group.

Figure 10 shows the breakpoint temperatures for the shale fuels plotted against weight percent nitrogen. The low-severity treated shale fuels, with nitrogen levels of 0.1 to 0.24 weight percent, had thermal breakpoint temperatures in the 477 to 505 K (400° to 450° F) range. The higher severity treated fuels, with nitrogen levels of 0.008 to 0.17 weight percent, had breakpoint temperatures in the 505 to 533 K (450° to 500° F) range. The fuels with nitrogen levels below 0.008 weight percent generally had breakpoint temperatures in excess of 533 K (500° F). There was little variation in the weight percent hydrogen in the shale fuels, and the sulfur levels were all below 0.0044 weight percent.

The coal-derived fuel samples all have very low nitrogen levels. The ARCO samples were less than or equal to 6 ppm, the Exxon samples were less than or equal to 67 ppm. Figure 11 shows the variation of thermal breakpoint temperature with hydrogen content for the low-nitrogen content fuels. In figure 11(a), which shows the coal fuels only, the samples show an increasing level for the breakpoint temperature with increasing weight percent hydrogen. Except for the synthoil, fuels with the hydrogen content below 13.0 weight percent had breakpoint temperatures below 533 K (500° F); only two of the coal-derived fuels with H $\geq$ 13.5 weight percent had breakpoint temperatures below 533 K (500° F). One of these two was the sample that had the breakpoint temperature determined by the ΔP across the test filter rather than by tube deposit rating. The synthoil-derived fuels have a significantly higher level of breakpoint temperature for the same hydrogen content. Synthoil fuel samples with hydrogen levels of 12 to 12.3 weight percent had breakpoint temperatures equal to or greater than 533 K (500° F).

Figure 11(b) shows the breakpoint temperature data for the few shale-derived fuels which had nitrogen contents less than or equal to 67 ppm superimposed on the coal fuels plot. Of the five shale fuels that met this low nitrogen criterion, only one (a low-severity treated fuel) had a breakpoint temperature significantly below the general level of the coal fuel data.

CONCLUDING REMARKS

This report has presented thermal stability breakpoint temperature data, obtained on the ALCOR JFTOT apparatus, for 32 aircraft turbine type fuels prepared from shale and coal syncrudes. These fuels were the result of specifying the yield and severity of hydroprocessing. The final fuel samples represented four different distillation ranges for each processing sequence, nominally 366 to 561 K (200° to 550° F), 366 to 616 K (200° to 650° F), 422 to 561 K (300° to 550° F), and 422 to 616 K (300° to 650° F).

The shale-derived fuels showed a variation in breakpoint temperature with nitrogen content. The higher nitrogen level fuels, 0.1 to 0.24 weight percent nitrogen, had breakpoint temperatures in the 477 to 505 K (400° to 450° F) range. The lower nitrogen level fuels, 0.008 to 0.017 weight percent, had breakpoint temperatures in the 505 to 533 K (450° to 500° F) range. With the shale-derived fuels of nitrogen content less than about 0.008 weight percent nitrogen, there appeared to be no general trend of breakpoint temperature with nitrogen content.

The improved thermal stability with reduced nitrogen content does not prove that nitrogen containing compounds are the sole, or even major, contributors to thermal instability. The increased hydrogenation severity that is required to reduce the nitrogen content should also reduce the concentrations of other unstable species such as oxygen containing organics or olefinic hydrocarbons.

The nitrogen levels of the coal-derived fuels were all fairly low, less than 70 ppm. The breakpoint temperatures of the coal-derived fuels showed generally increasing breakpoint temperature with increasing weight percent hydrogen, although the correlation is not a very strong one. None of the ARCO fuels below 13.0 weight percent hydrogen had breakpoints equal to or greater than 533 K (500° F), and only two of the coal fuels with hydrogen content greater than or equal to 13.5 weight percent hydrogen had breakpoint temperatures below 533 K (500° F). There appears to be a significantly higher level of breakpoint temperature for the Exxon Synthoil derived fuels than for the other coal-derived fuels for the same hydrogen content. The Synthoil fuels with hydrogen levels of 12 to 12.3 weight percent had breakpoint temperatures equal to or greater than 533 K (500° F).

Again, the improved thermal stability with increased hydrogen content is not necessarily the result of hydrogen concentration alone, but more probably it results from the saturation or removal of trace amounts of unstable species by more drastic hydrogenation.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 17, 1977,
505-04.

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TABLE I. - FINAL PRODUCT INSPECTIONS

Data from ref. 1.

(a) Low yield shale products

Property	Low severity				High severity			
	Boiling range, K (°F)							
	IBP-616 (IBP-560)	394 to 616 (250 to 650)	394 to 561 (250 to 550)	IBP-561 (IBP-550)	IBP-616 (IBP-650)	394 to 615 (250 to 650)	394 to 561 (250 to 550)	IBP-561 (IBP-550)
	Fuel number							
	33315	33316	33317	33318	33340	33341	33342	33343
Specific gravity	0.8040	0.8170	0.8068	0.7945	0.7977	0.8081	0.8022	0.7914
Reid vapor pressure, kN/m^2 (psi)	1.1 (0.15)	----------	----------	0.34 (0.05)	2.8 (0.40)	----------	----------	1.1 (0.15)
Flash point, K (°F)	---------	315 (108)	311 (100)	----------	---------	312 (102)	312 (102)	---------
Freezing point, K (°F)	255 (0)	258 (5)	229 (-47)	225 (-54)	255 (1)	258 (5)	231 (-44)	229 (-47)
Viscosity at 239 K (-30° F), m^2/sec	(a)	(a)	6.781×10^{-6}	4.736×10^{-6}	(a)	(a)	6.990×10^{-6}	5.059×10^{-6}
Net heat of combustion, J/g	43 836	43 652	44 120	43 631	44 120	43 857	43 190	43 928
Existing gum, mg	16.2	51.4	40.2	32.2	0.8	19.2	8.6	9.0
Smoke point	21	20	21	22	26	26	24	26
Aromatics, percent	21.9	25.9	22.2	19.0	13.7	17.4	17.1	13.5
Olefins, percent	1.1	0.8	1.1	1.0	0.8	1.0	1.2	0.9
Naphthalenes, percent	1.0	1.2	0.5	0.5	0.4	0.4	0.2	0.2
Hydrogen, percent	13.64	13.66	13.68	13.73	13.82	13.86	13.95	13.76
Nitrogen, percent	0.1954	0.2233	0.2011	0.1750	0.0161	0.0168	0.0152	0.0132
Total sulfur, percent	0.0010	0.0044	0.0006	0.0006	0.0009	0.0003	0.0001	0.0002
Mercaptans, percent	0.0002	0.0002	0.0002	0.0002	0.0003	0.0002	----------	---------
Oxygen, percent	0.03	0.05	0.06	0.04	0.03	0.05	0.09	0.09

[a]Solid.

TABLE I. - Continued.

(b) High yield shale products

Property	Low severity				High severity			
	Boiling range, K (°F)							
	IBP-616 (IBP-650)	394 to 616 (250 to 650)	394 to 561 (250 to 550)	IBP-561 (IBP-550)	IBP-616 (IBP-650)	394 to 616 (250 to 650)	394 to 561 (250 to 550)	IBP-561 (IBP-550)
	Fuel number							
	33365	33366	33367	33368	33408	33409	33410	33411
Specific gravity	0.7972	0.8146	0.8054	0.7874	0.7936	0.8100	0.8035	0.7874
Reid vapor pressure, kN/m^2 (psi)	7.6 (1.10)	----------	----------	6.9 (1.00)	8.6 (1.25)	----------	----------	7.6 (1.10)
Flash point, K (°F)	----------	314 (106)	312 (102)	----------	----------	312 (102)	309 (96)	----------
Freezing point, K (°F)	251 (-8)	255 (-1)	227 (-50)	222 (-59)	250 (-9)	254 (-3)	226 (-52)	223 (-58)
Viscosity at 239 K (-30° F), m^2/sec	(a)	(a)	6.918×10^{-6}	4.093×10^{-6}	----------	----------	7.060×10^{-6}	4.326×10^{-6}
Net heat of combustion, J/g	44 204	44 062	----------	44 442	44 329	43 882	44 066	44 371
Existing gum, mg	26.8	61.8	23.4	17.0	9.2	32.8	16.0	16.6
Smoke point	23	20	22	25	26	25	25	27
Aromatics, percent	15.7	20.3	17.9	13.7	12.1	15.4	13.2	11.4
Olefins, percent	0.8	0.9	1.3	0.8	0.6	1.0	1.0	0.8
Naphthalenes, percent	0.75	0.93	0.42	0.33	0.3	0.35	0.21	0.17
Hydrogen, percent	13.82	13.37	13.80	13.70	13.98	13.95	13.95	13.98
Nitrogen, percent	0.1305	0.1581	0.1397	0.1138	0.0101	0.0144	0.0076	0.0088
Total sulfur, percent	0.0014	0.0012	0.0006	0.0005	0.0011	0.0002	0.0002	0.0002
Mercaptans, percent	0.0001	----------	----------	----------	<0.0001	----------	----------	----------
Oxygen, percent	0.08	0.14	0.14	0.13	0.11	0.10	0.07	0.10

[a]Solid.

TABLE I. - Continued.

(c) Low yield H-Coal products

Property	Low severity				High severity			
	Boiling range, K (°F)							
	IBP-616 (IBP-650)	394 to 616 (250 to 653)	394 to 561 (250 to 550)	IBP-561 (IBP-550)	IBP-616 (IBP-650)	394 to 616 (250 to 650)	394 to 561 (250 to 550)	IBP-561 (IBP-550)
	Fuel number							
	33416	33417	33418	33419	33430	33431	33432	33433
Specific gravity	0.8493	0.8654	0.8565	0.8413	0.8338	0.8488	0.8468	0.8314
Reid vapor pressure, kN/m^2 (psi)	1.4 (0.20)	----------	----------	1.1 (0.15)	1.7 (0.25)	----------	----------	3.1 (0.45)
Flash point, K (°F)	----------	312 (102)	309 (96)	----------	----------	312 (102)	314 (106)	----------
Freezing point, K (°F)	251 (-8)	237 (-32)	217 (-68)	211 (-79)	255 (0)	246 (-17)	225 (-54)	207 (-86)
Viscosity at 239 K (-30° F), m^2/sec	----------	16.99×10^{-6}	6.785×10^{-6}	5.162×10^{-6}	9.757×10^{-6}	15.91×10^{-6}	9.102×10^{-6}	6.264×10^{-6}
Net heat of combustion, J/g	43 359	42 878	43 108	43 263	43 723	43 273	43 273	43 601
Existing gum, mg	6.0	74.0	92.0	10.2	4.8	110.8	11.2	9.8
Smoke point	14	15	15	16	24	21	24	25
Aromatics, percent	29.7	33.8	30.9	26.3	5.9	6.7	5.8	5.5
Olefins, percent	1.2	1.8	1.4	1.2	1.3	1.4	1.0	0.9
Naphthalenes, percent	0.54	0.66	0.31	0.27	0.064	0.077	0.065	0.055
Hydrogen, percent	12.73	12.47	12.64	12.79	13.56	13.26	13.31	13.73
Nitrogen, percent	0.0005	0.0006	0.0006	0.0001	<0.0001	<0.0001	<0.0001	0.0001
Total sulfur, percent	0.0004	0.0004	0.0001	0.0001	0.0005	0.0005	<0.0001	0.0001
Mercaptans, percent	----------	----------	----------	----------	----------	----------	----------	----------
Oxygen, percent	0.11	0.09	0.06	0.10	0.04	0.06	0.03	0.04

TABLE I. - Concluded.

(d) High yield COED products

Property	High severity				Low severity			
	Boiling range, K (°F)							
	IBP-616 (IBP-650)	394 to 616 (250 to 650)	394 to 561 (250 to 550)	IBP-561 (IBP-550)	IBP-616 (IBP-650)	394 to 616 (250 to 650)	394 to 561 (250 to 550)	IBP-561 (IBP-550)
	Fuel numbers							
	33502	33503	33504	33505	33516	33517	33518	33519
Specific gravity	0.8255	0.8458	0.8368	0.8165	0.8358	0.8586	0.8493	0.8270
Reid vapor pressure, kN/m^2 (psi)	5.8 (0.85)	----------	----------	5.8 (0.85)	5. (0.85)	----------	----------	7.2 (1.05)
Flash point, K (°F)	----------	313 (104)	314 (106)	----------	----------	319 (114)	313 (104)	----------
Freezing point, K (°F)	242 (-23)	239 (-30)	220 (-64)	215 (-72)	256 (-23)	256 (2)	221 (-62)	217 (-70)
Viscosity at 239 K (-30° F), m^2/sec	(a)	19.25×10^{-6}	9.676×10^{-6}	5.565×10^{-6}	(a)	(a)	9.851×10^{-6}	5.586×10^{-6}
Net heat of combustion, J/g	43 865	44 074	43 865	44 129	43 212	43 627	43 518	43 873
Existing gum, mg	0.8	23.0	6.6	7.6	1.6	21.2	2.4	3.2
Smoke point	20	20	24	27	16	14	16	19
Aromatics, percent	9.3	11.6	7.2	5.4	22.4	28.5	25.2	20.1
Olefins, percent	0.7	1.1	0.9	0.5	0.6	1.2	0.8	0.5
Naphthalenes, percent	0.49	0.62	0.13	0.11	0.68	0.86	0.38	0.31
Hydrogen, percent	13.6	13.44	13.63	13.69	13.07	12.88	12.96	13.24
Nitrogen, percent	0.0002	0.0002	0.0002	0.0002	0.0003	0.0002	0.0002	0.0002
Total sulfur, percent	0.0003	0.0003	0.0001	0.0001	0.0003	0.0001	0.0001	0.0001
Mercaptans, percent	----------	----------	----------	----------	----------	----------	----------	----------
Oxygen, percent	0.05	0.05	0.05	0.03	0.03	0.03	0.03	0.03

[a]Solid.

TABLE II. - ARCO FUEL SAMPLES

ARCO number	Crude	Yield level	Severity level	ASTM boiling range		Weight percent			Jet fuel thermal oxidation tester breakpoint temperature		Jet fuel thermal oxidation tester visual rating at 533 K (500° F)	Process conditions				
												Pressure		Temperature		Space velocity, WHSV, hr^{-1}
				K	°F	H	N	S	K	°F		N/m^2	psi	K	°F	
33315	TOSCO	Low	Low	372 to 594	211 to 610	13.64	0.195	0.001	491	424	4	10.3×10^6	1500	625	665	1.5
33316	↓	↓	↓	425 to 596	305 to 613	13.66	.2233	.0044	495	431	4					
33317				425 to 543	305 to 518	13.68	.2011	.0006	501	442	4					
33318				374 to 545	213 to 521	13.73	.175	.0006	495	431	1					
33340	TOSCO	Low	High	377 to 594	219 to 610	13.82	0.016	0.0009	515	467	na[a]	10.3×10^6	1500	652	715	1.5
33341	↓	↓	↓	424 to 596	303 to 613	13.86	.0168	.0003	514	466	4					
33342				424 to 550	304 to 531	13.95	.0152	.0001	535	504	3					
33343				380 to 554	224 to 537	13.76	.013	.0002	516	469	4					
33365	TOSCO	High	Low	349 to 591	168 to 605	13.82	0.131	0.0014	485	414	4	13.8×10^6	2000	[b](666 to 675 622)	[b](740 to 755 660)	[b](0.36 to 0.43 0.75)
33366	↓	↓	↓	422 to 593	301 to 608	13.37	.1581	.0012	480	405	4					
33367				423 to 550	302 to 530	13.80	.1397	.0006	509	456	4					
33368				350 to 549	170 to 528	13.70	.114	.0005	502	444	4					
33408	TOSCO	High	High	352 to 592	175 to 607	13.98	0.010	0.0011	524	483	4	13.8×10^6	2000	[b](666 to 675 622)	[b](740 to 755 660)	[b](0.36 to 0.43 0.75)
33409	↓	↓	↓	424 to 594	304 to 609	13.95	.0144	.0002	521	478	4					
33410				425 to 552	306 to 535	13.95	.0076	.0002	506	452	4					
33411				369 to 552	204 to 534	13.98	.0088	.0002	514	465	4					
33416	H-Coal	Low	Low	376 to 624	218 to 663	12.73	0.0005	0.0004	510	458	4	13.8×10^6	2000	611	640	0.5
33417	↓	↓	↓	na	na	12.47	.0006	.0004	509	456	4					
33418				416 to 550	290 to 531	12.64	.0006	.0001	508	455	4					
33419				380 to 557	225 to 543	12.79	.0001	.0001	516	470	3					
33430	H-Coal	Low	High	383 to 615	230 to 648	13.56	<0.0001	0.0001	525	485	0	17.2×10^6	2500	630 to 636	675 to 685	0.5 to 0.45
33431	↓	↓	↓	424 to na	304 to na	13.26	<.0001	.0005	>561	550	1					
33432				424 to 545	304 to 522	13.31	<.0001	<.0001	>561	550	0					
33433				380 to 558	224 to 545	13.73	.0005	.0001	>583	590	1					
33502	COED	High	High	360 to 592	188 to 606	13.6	0.0002	0.0003	541	515	0	13.8×10^6	2000	[c](641 to 647) [d](658 to 675) [e](609 to 631)	[c](695 to 705) [d](725 to 755) [e](636 to 676)	[c]0.5 [d]0.7 [e]1.0
33503	↓	↓	↓	425 to 593	305 to 608	13.44	.0002	.0003	517	471	3					
33504				427 to 551	309 to 533	13.63	.0002	.0001	553	536	2					
33505				360 to 557	189 to 544	13.69	.0002	.0001	589	600	1					
33516	COED	High	Low	362 to 591	192 to 605	13.07	0.0003	0.0003	536	506	0	13.8×10^6	2000	[c](616 to 622) [d](658 to 664) [e](607 to 631)	[c](650 to 660) [d](725 to 735) [e](634 to 676)	[c](0.65 to 0.8) [d]0.7 [e]1.0
33517	↓	↓	↓	425 to na	305 to na	12.88	.0002	.0001	512	506	3					
33518				424 to 551	304 to 532	12.96	.0002	.0001	541	514	4					
33519				360 to 553	189 to 536	13.24	.0002	.0001	548	527	0					

[a]Not available, na.

[b]Hydrotreatment and hydrocracking conditions. Final sample blends also contain low-yield material.

[c]Hydrotreatment of IBP to 561 K (IBP to 550° F) fraction.
[d]Hydrotreatment of 561 to 700 K (550° to 800° F) fraction.
[e]Hydrotreatment of 561 to 700 K (550° to 800° F) fraction
(c, d, e:) Final sample blends contain products from treatment of both fractions.

TABLE III. - EXXON FUEL SAMPLES

[Data from ref. 5.]

EXXON number	Crude	Fuel type	Severity level	ASTM boiling range		Weight percent			Jet fuel thermal oxidation tester breakpoint temperature		Process conditions				
											Pressure		Temperature		Space velocity, LHSV, hr^{-1}
				K	°F	H	N	S	K	°F	N/m^2	psi	K	°F	
113	TOSCO	JP-4	Low	384 to 517	231 to 471	13.05	0.0093	0.0005	552	534	5.5×10^6	800	644	700	1.2
113	↓	Jet A	Low	443 to 539	338 to 511	13.41	.017	.0012	523	482	5.5	800	↓	↓	1.2
17-B	↓	JP-4	Medium	384 to 521	231 to 478	14.3	.0062	.0003	577	580	10.3	1500	↓	↓	.93
17-B	↓	Jet A	Medium	445 to 540	342 to 512	13.87	.0063	.0009	637	688	10.3	1500	↓	↓	.93
410	↓	JP-4	High	395 to 516	252 to 469	-----	.0019	.0011	>541	>515	15.1	2200	↓	↓	.56
410	↓	Jet A	High	438 to 534	329 to 501	-----	.0034	.0008	>575	>575	15.1	2200	↓	↓	.56
111	Paraho	Jet A	Low	437 to 536	328 to 505	13.02	0.24	------	477	400	5.5×10^6	800	644	700	1.08
11-B	Paraho	Jet A	Medium	463 to 527	374 to 490	13.45	.0036	0.0004	572	570	10.3	1500	644	700	.93
414	Paraho	Jet A	High	451 to 523	352 to 482	-----	.0032	<.0001	>583	>590	15.1	2200	644	700	[a](0.35 to 0.50)
115	Garrett	Jet A	Low	434 to 542	321 to 517	13.41	0.0052	0.0019	502	445	5.5×10^6	800	644	700	0.91
103	↓	Jet A	Medium	447 to 534	345 to 502	13.58	.0030	.0004	586	585	10.3	1500	↓	↓	.99
404	↓	JP-4	High	392 to 533	246 to 500	-----	.0027	.0056	[b]>533	[b]>500	15.1	2200	↓	↓	.48
404	↓	Jet A	High	454 to 530	358 to 495	-----	.0026	.0036	>597	>615	15.1	2200	↓	↓	.48
405	↓	Jet A	High	459 to 526	366 to 488	-----	.0015	.0009	>602	>625	15.1	2200	↓	↓	.42
203	Synthoil	Jet A	Low	444 to 546	340 to 524	11.08	0.0067	0.0005	487	418	5.5×10^6	800	644	700	0.88
105	↓	↓	Medium	439 to 538	331 to 509	12.17	.0030	.0022	555	540	10.3	1500	↓	↓	.81
107	↓	↓	Medium	434 to 536	322 to 505	11.96	.0057	.0005	544	520	10.3	1500	↓	↓	.95
202	↓	↓	Medium	442 to 541	337 to 514	12.33	.0016	.0029	533	500	10.3	1500	↓	↓	.69
416	↓	↓	High	396 to 527	254 to 489	-----	.0029	.0004	>566	>560	15.1	2200	↓	↓	[a].54
304	H-Coal	JP-4	Low	369 to 490	205 to 422	12.61	0.0026	0.0003	519	475	5.5×10^6	800	644	700	0.99
304	↓	Jet A	Low	448 to 522	347 to 480	11.7	.0027	.0006	467	382	5.5	800	↓	↓	.99
209	↓	JP-4	Medium	361 to 492	190 to 427	14.29	.0024	.0001	552	535	10.3	1500	↓	↓	.95
209	↓	Jet A	Medium	444 to 520	340 to 476	12.66	.0047	.0016	536	505	10.3	1500	↓	↓	.95
419	↓	Jet A	High	452 to 519	354 to 474	-----	.0026	<.0001	541	>515	15.1	2200	↓	↓	.49[a]

[a]Final blends result from multistage treatments. Conditions cited here are for last stage only.
[b]Considered indeterminate due to excessive vaporization in test apparatus.

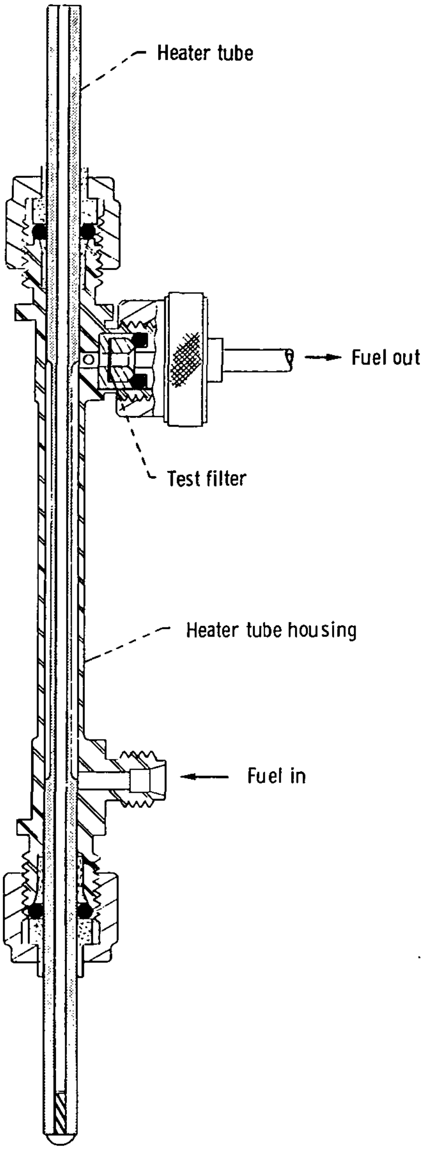


Figure 1. - Assembly drawing of heater tube section. Heated length, 6.0 centimeters; tube outside diameter, 0.325 centimeter; flow rate, 3.0 cubic centimeter per minute; residence time, 2.0 seconds per centimeter length; flow velocity, 0.5 centimeter per second.

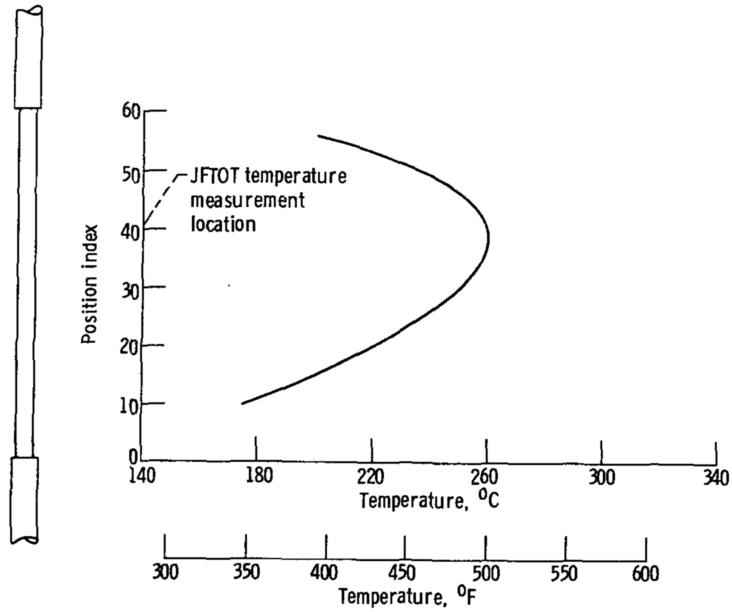


Figure 2. - Typical temperature profile in JFTOT tubes.

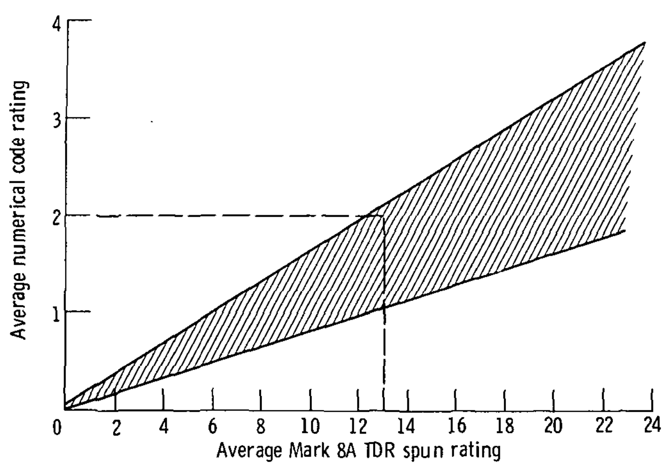
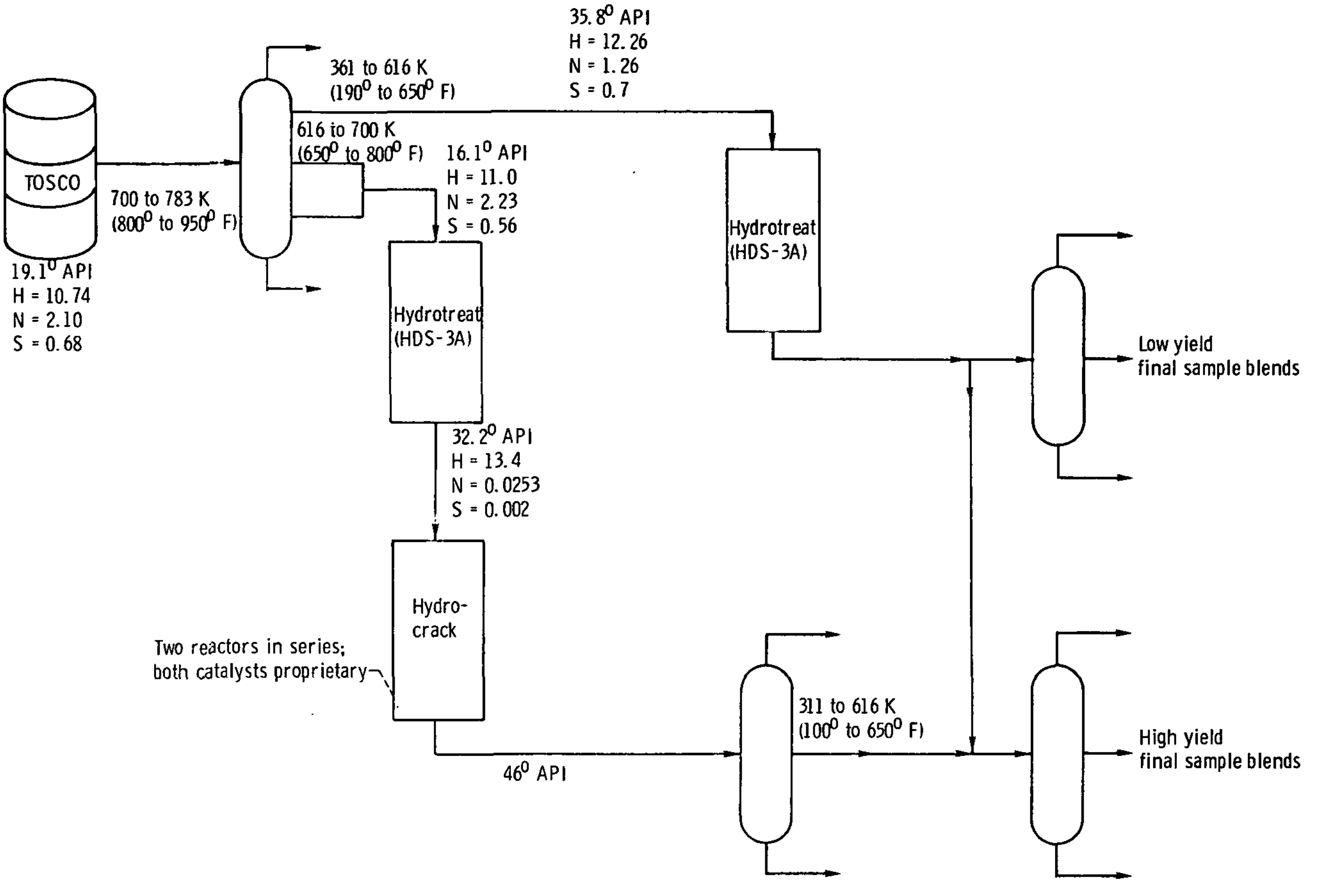
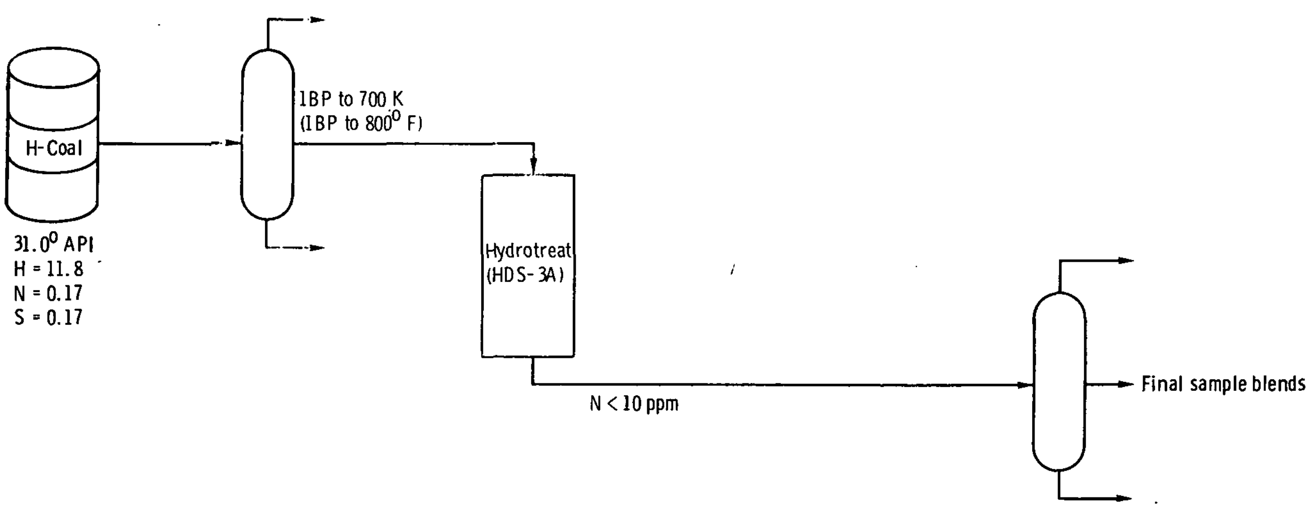


Figure 3. - Comparison of visual code ratings and Mark 8A spun ratings (from ref. 4).

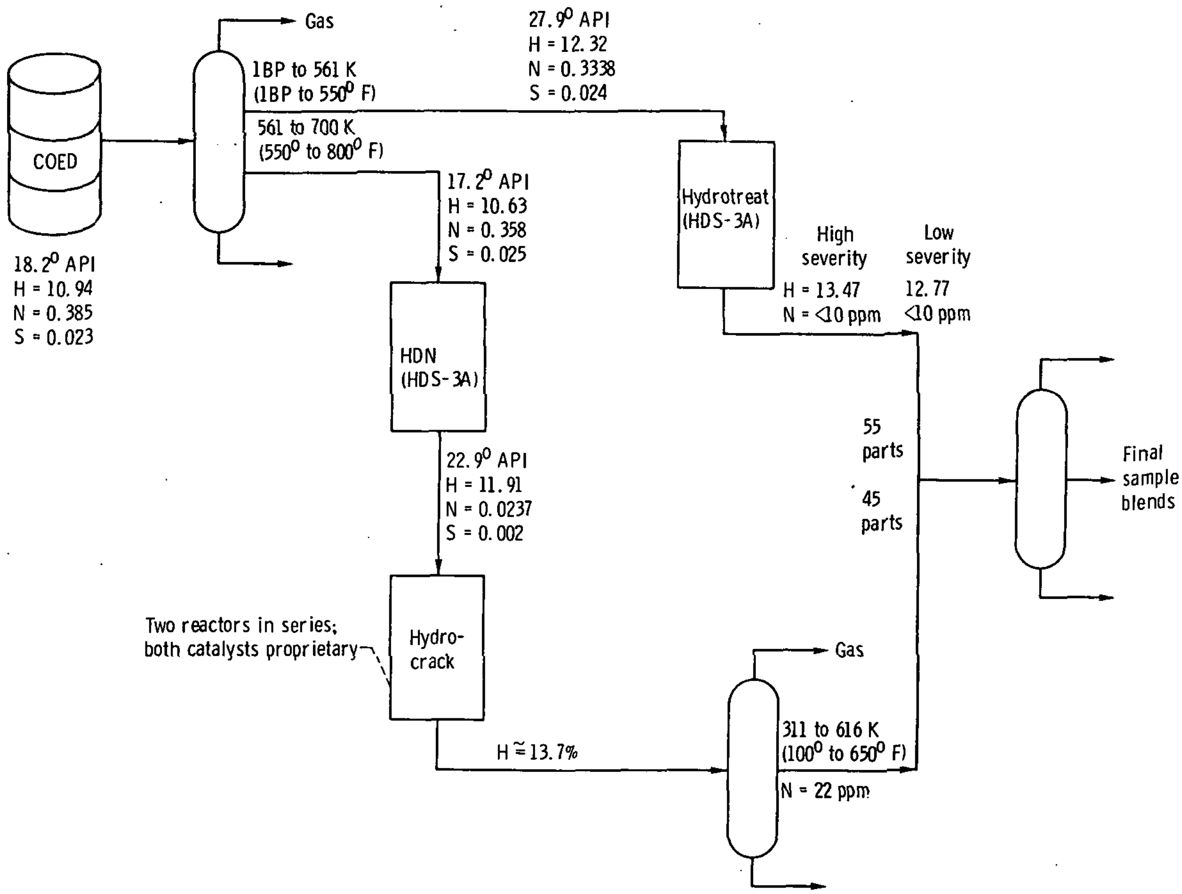


(a) TOSCO shale oil.



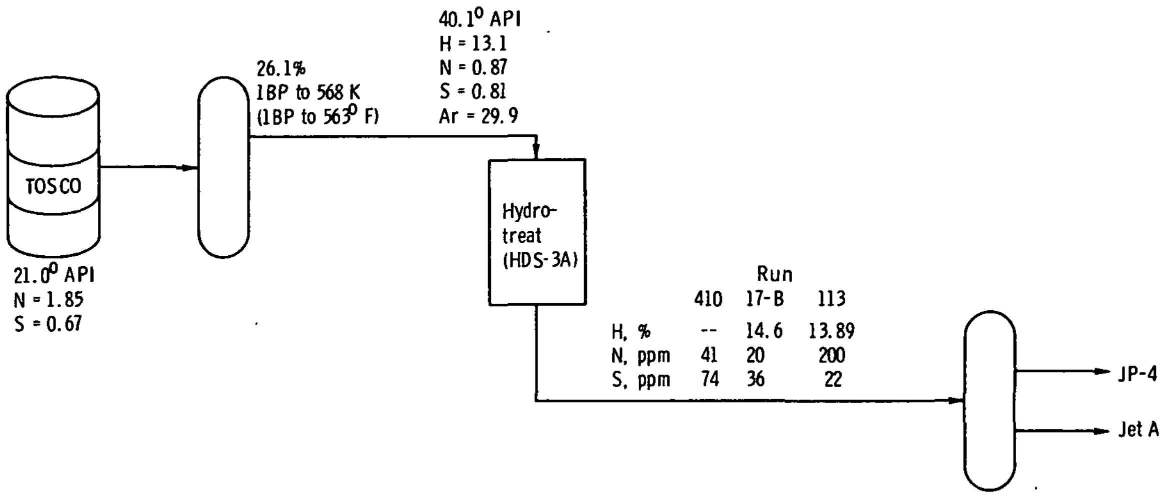
(b) H-Coal.

Figure 4. - Schematic diagram of ARCO product treatments.

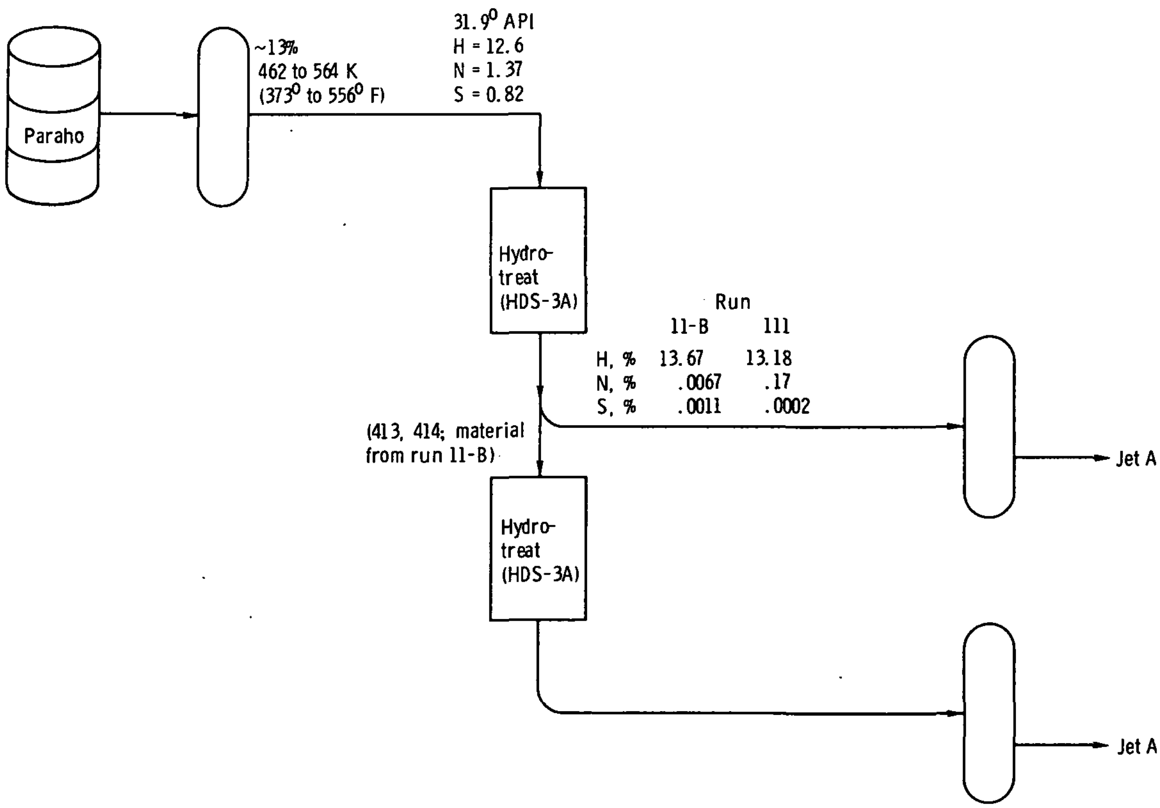


(c) COED.

Figure 4. - Concluded.

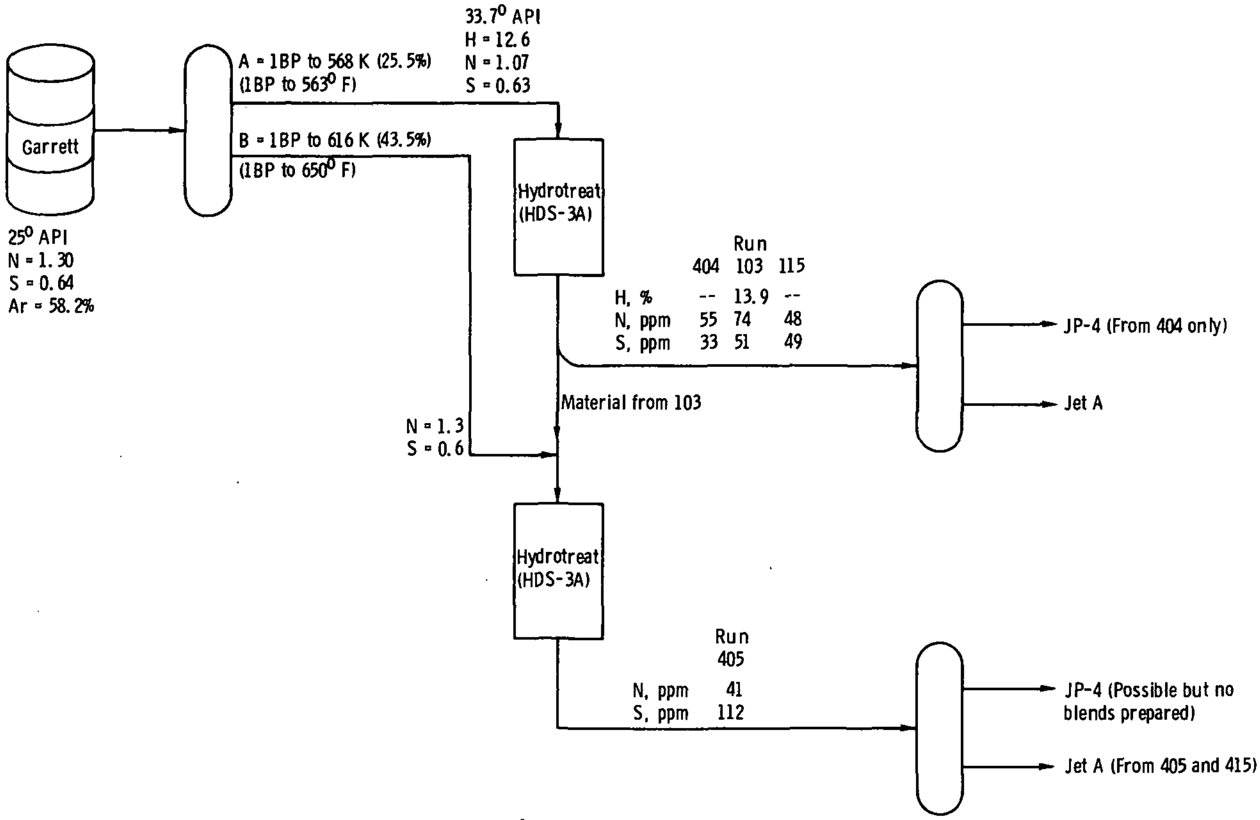


(a) TOSCO shale oil.



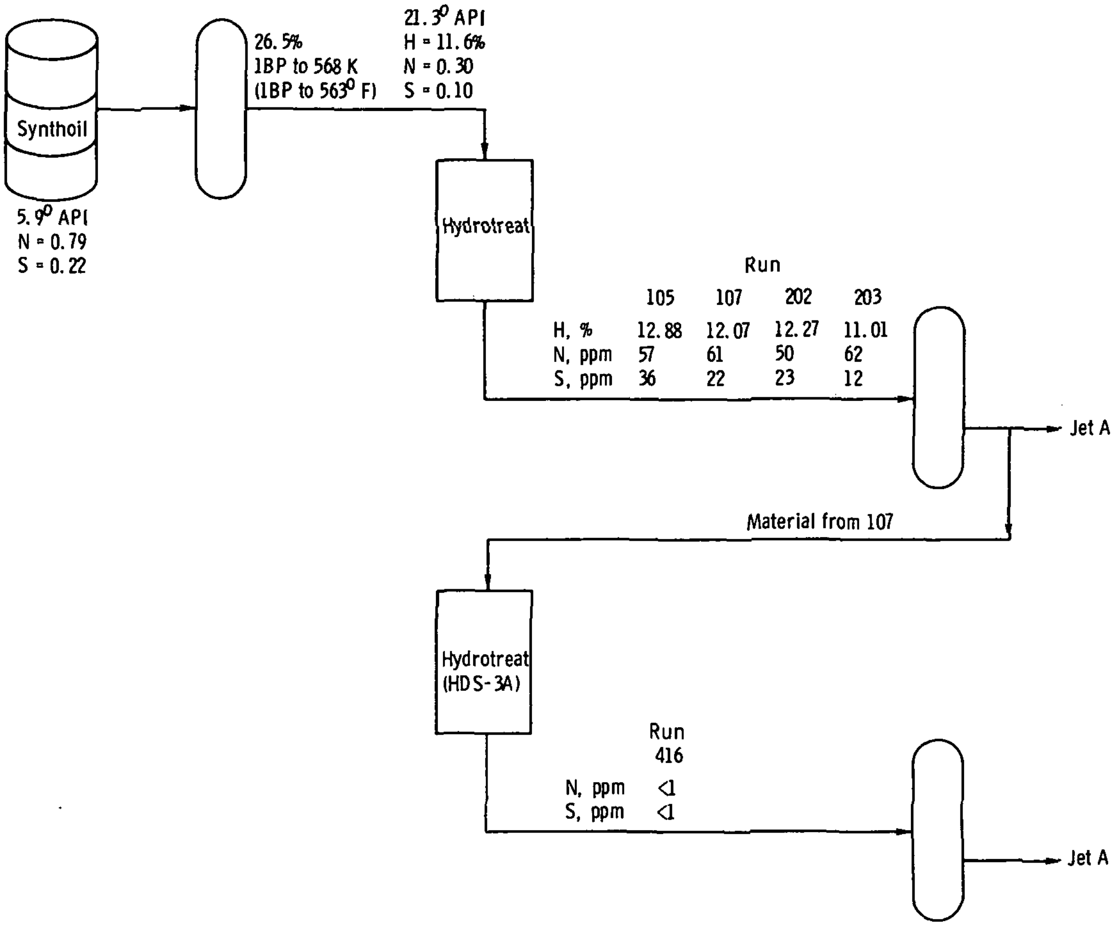
(b) Paraho shale oil.

Figure 5. - Schematic diagram of Exxon product treatments.



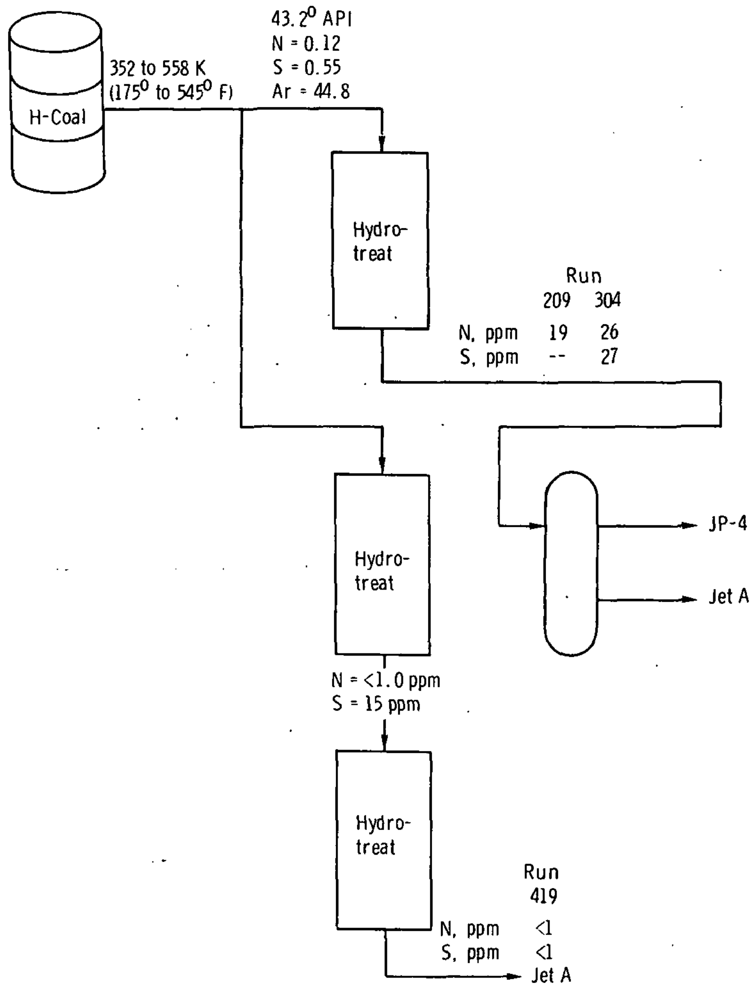
(c) Garrett shale oil.

Figure 5. - Continued.



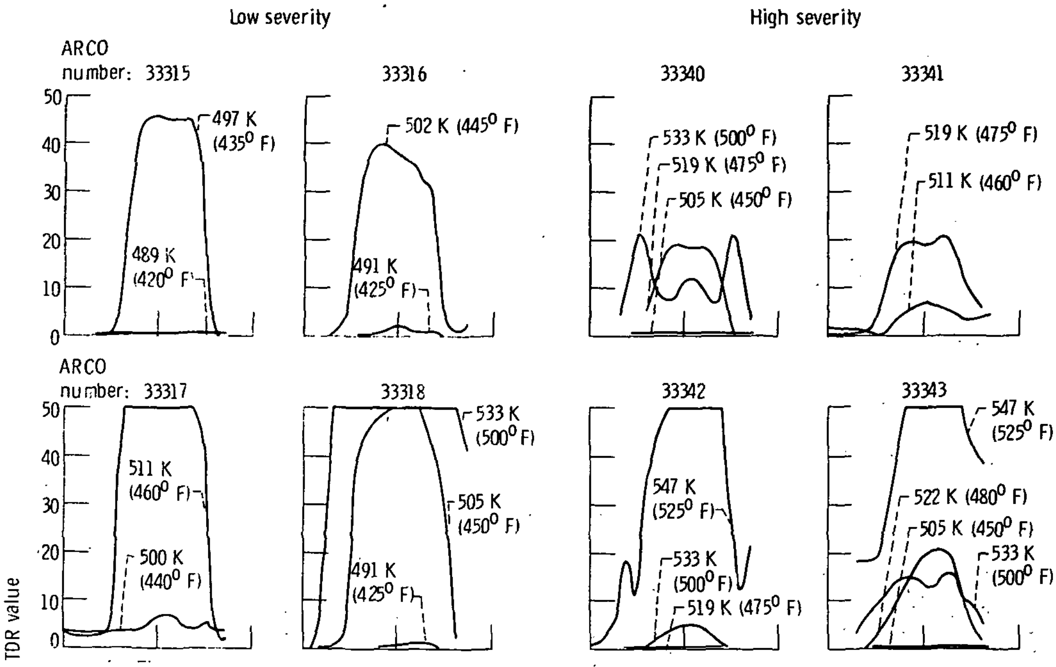
(d) Synthoil.

Figure 5. - Continued.

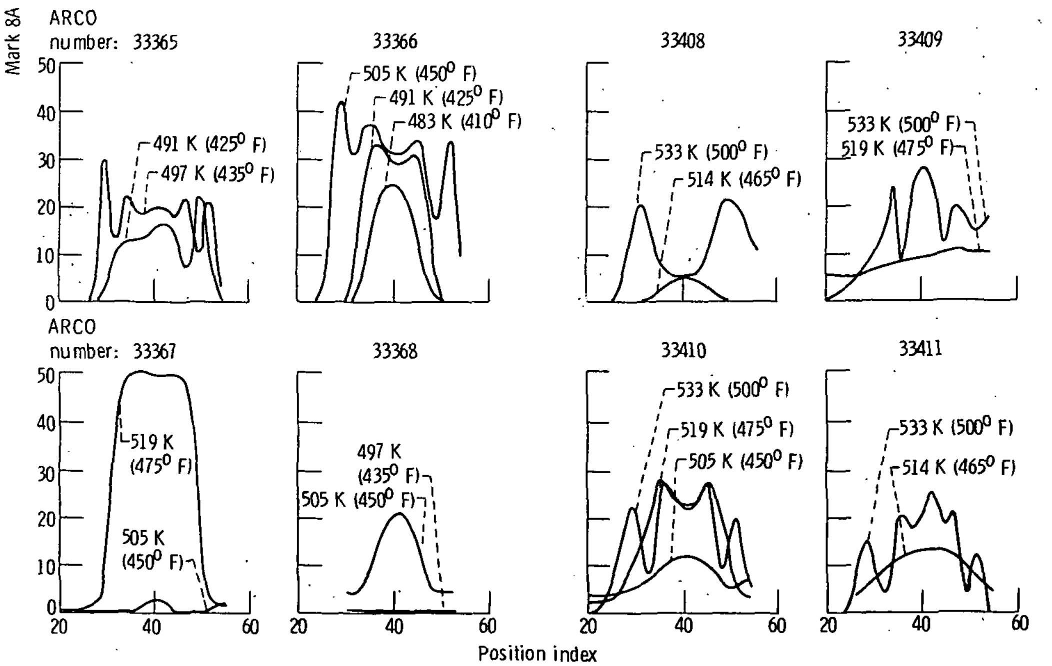


(e) H-Coal.

Figure 5. - Concluded.

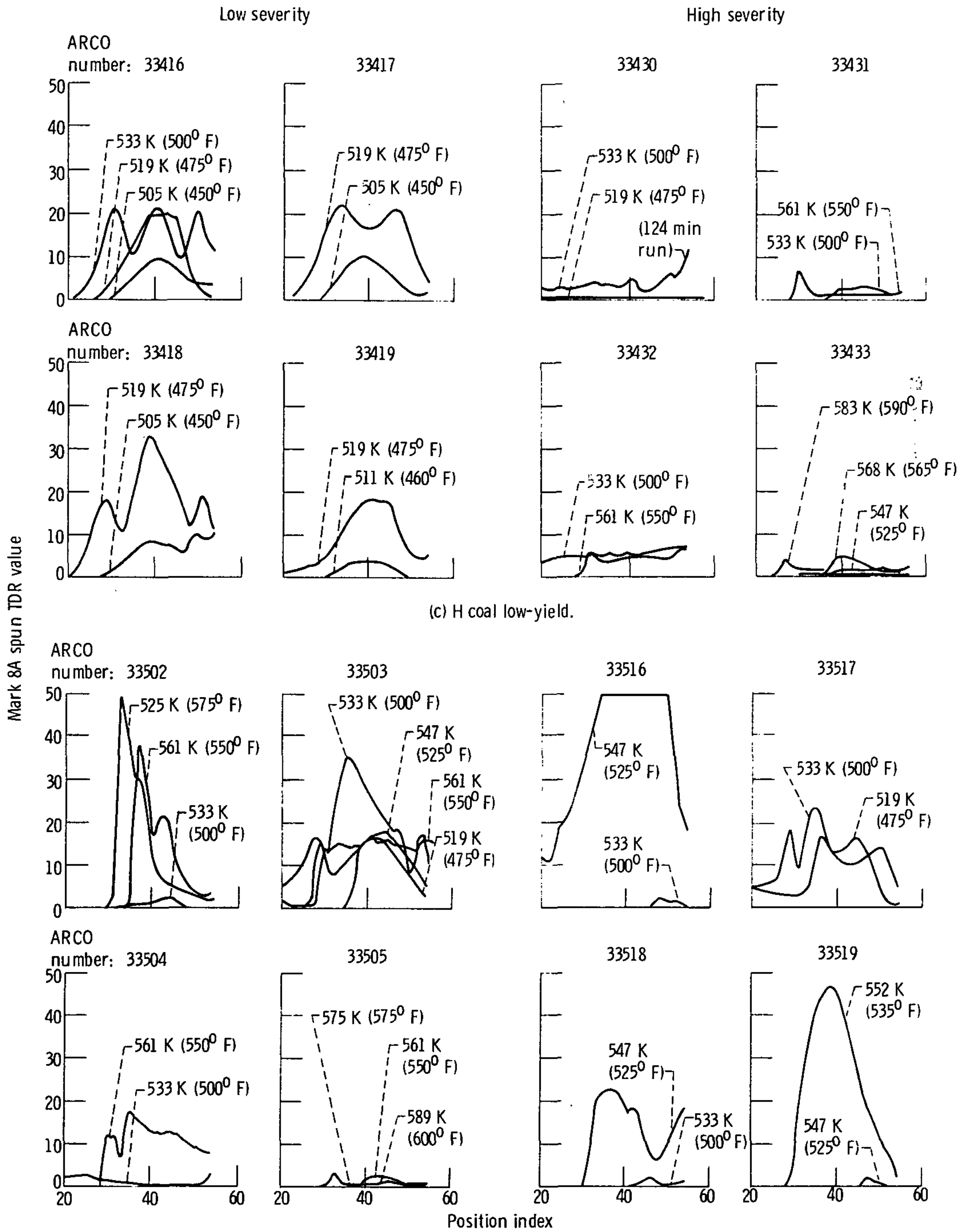


(a) TOSCO - low yield.



(b) TOSCO - high yield.

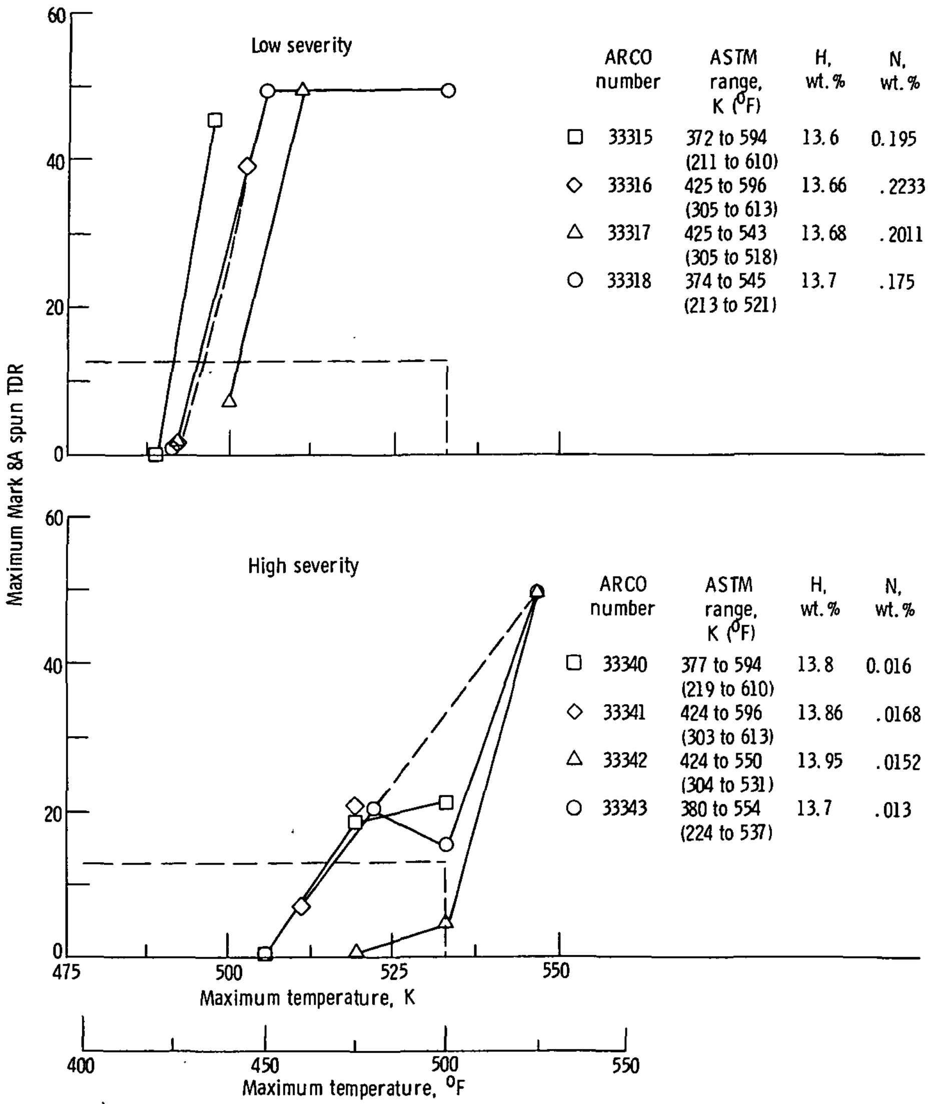
Figure 6. - Axial scan of Mark 8A spun tube deposit ratings.



(c) H coal low-yield.

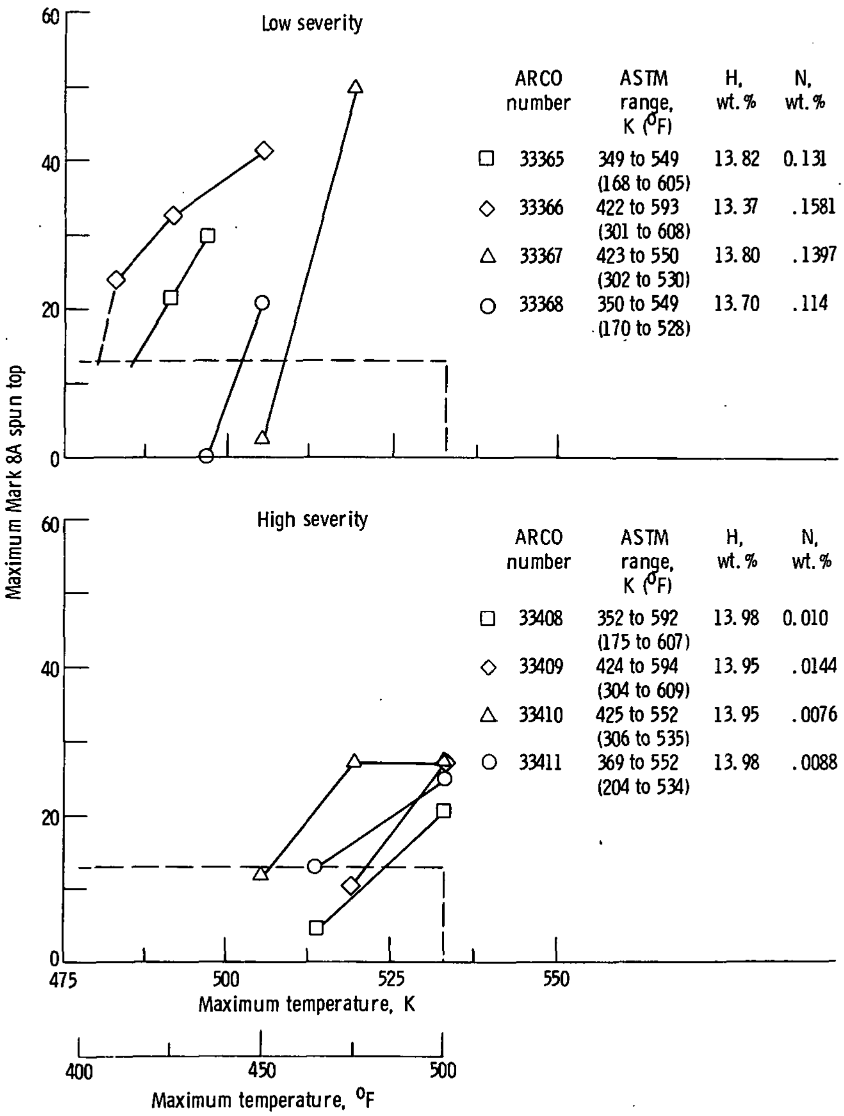
(d) COED high yield.

Figure 6. - Concluded.



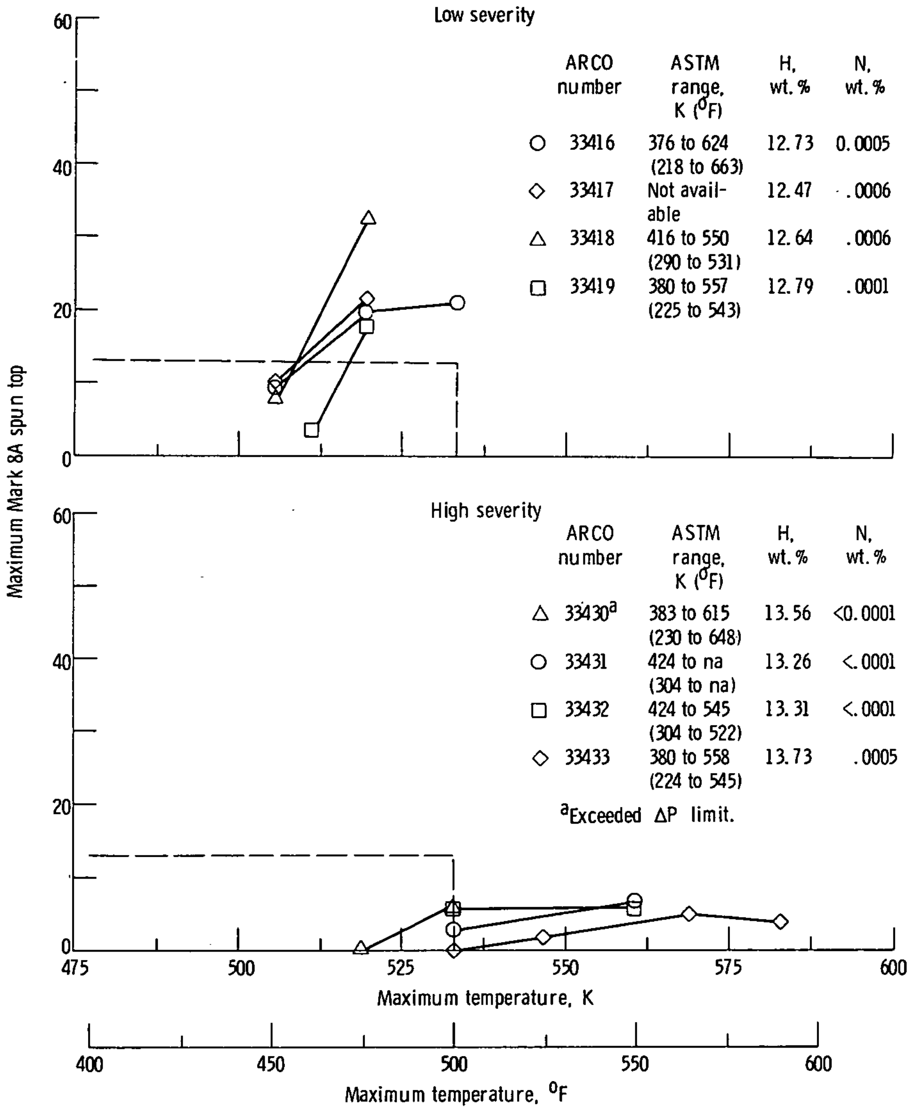
(a) TOSCO low yield.

Figure 7. - Variation of maximum Mark 8A spun TDR with temperature.



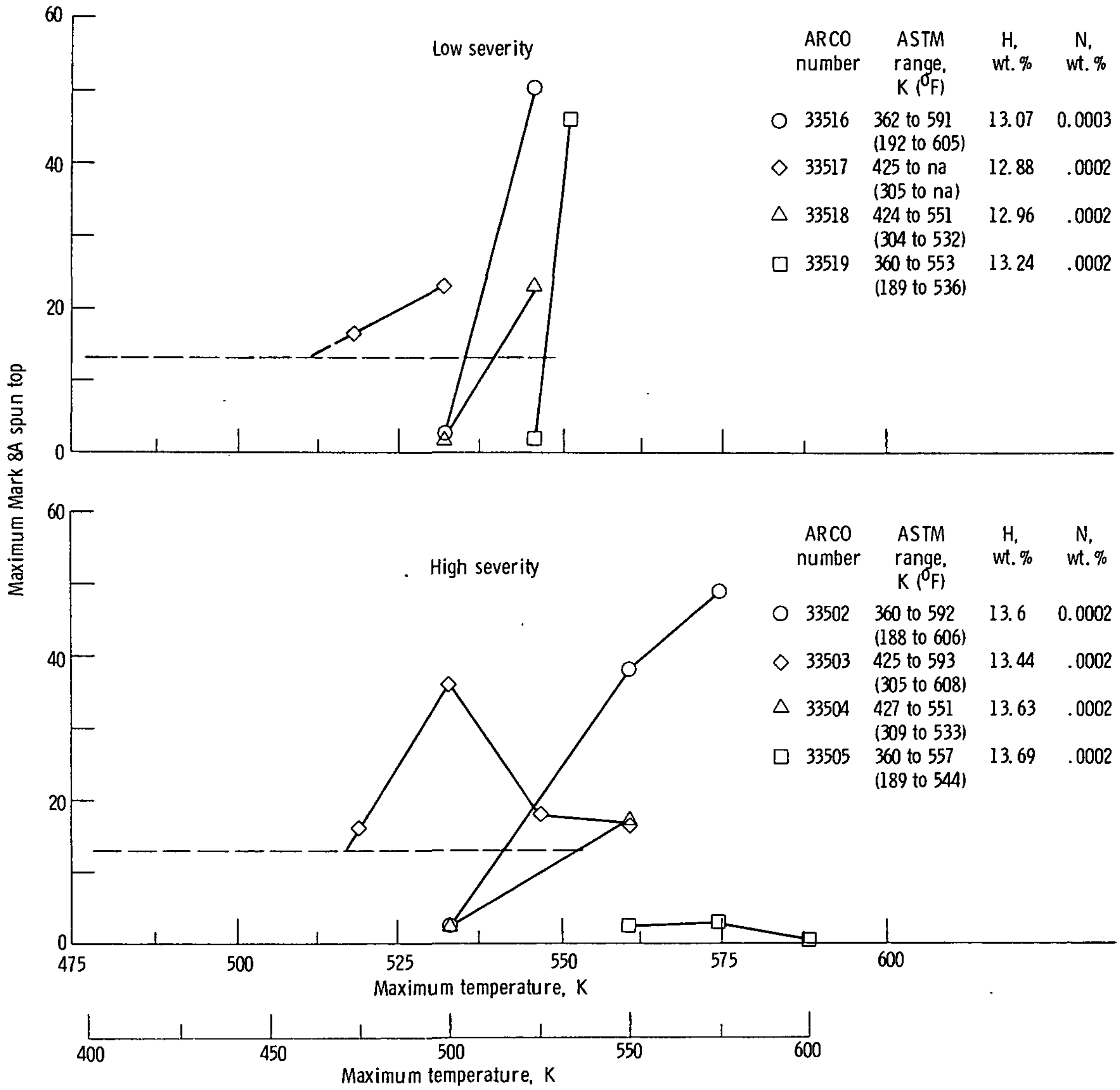
(b) TOSCO high yield.

Figure 7. - Continued.



(c) H-Coal low yield.

Figure 7. - Continued.



(d) COED high yield.

Figure 7. - Concluded.

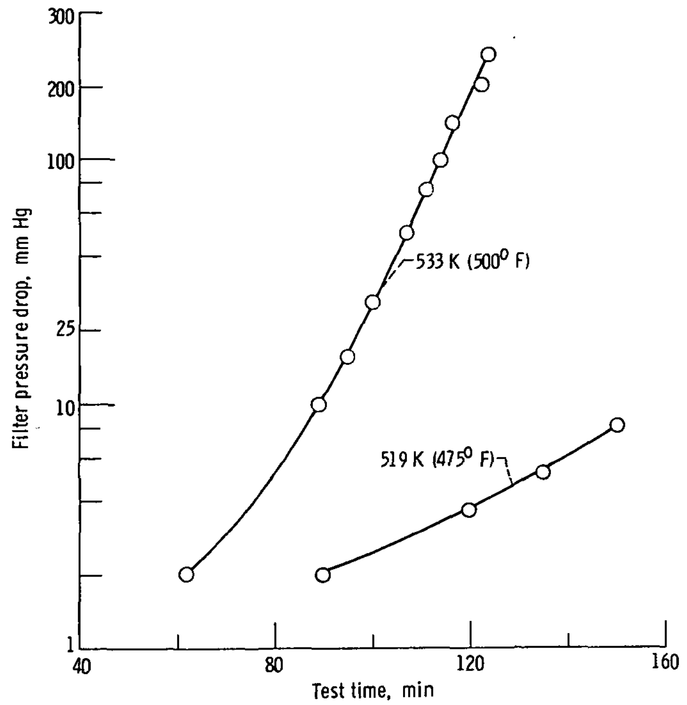


Figure 8. - Time variation of pressure drop through JFTOT test filter for ARCO sample 33430 (H-Coal).

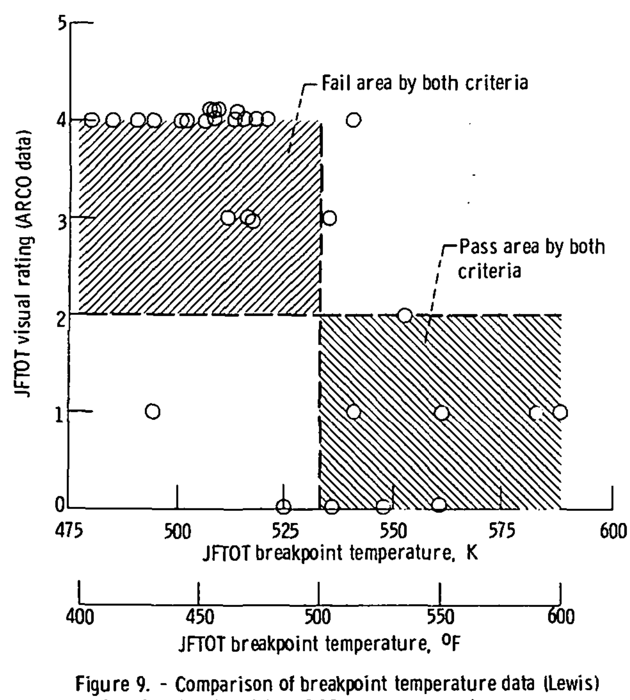


Figure 9. - Comparison of breakpoint temperature data (Lewis) with visual rating data (ARCO) on same sample.

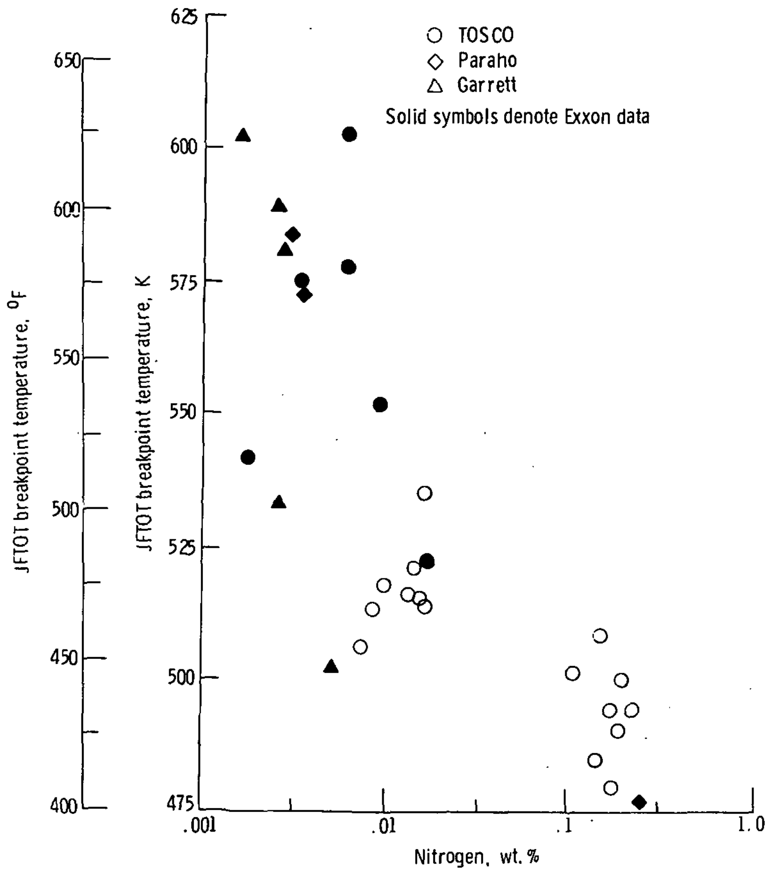
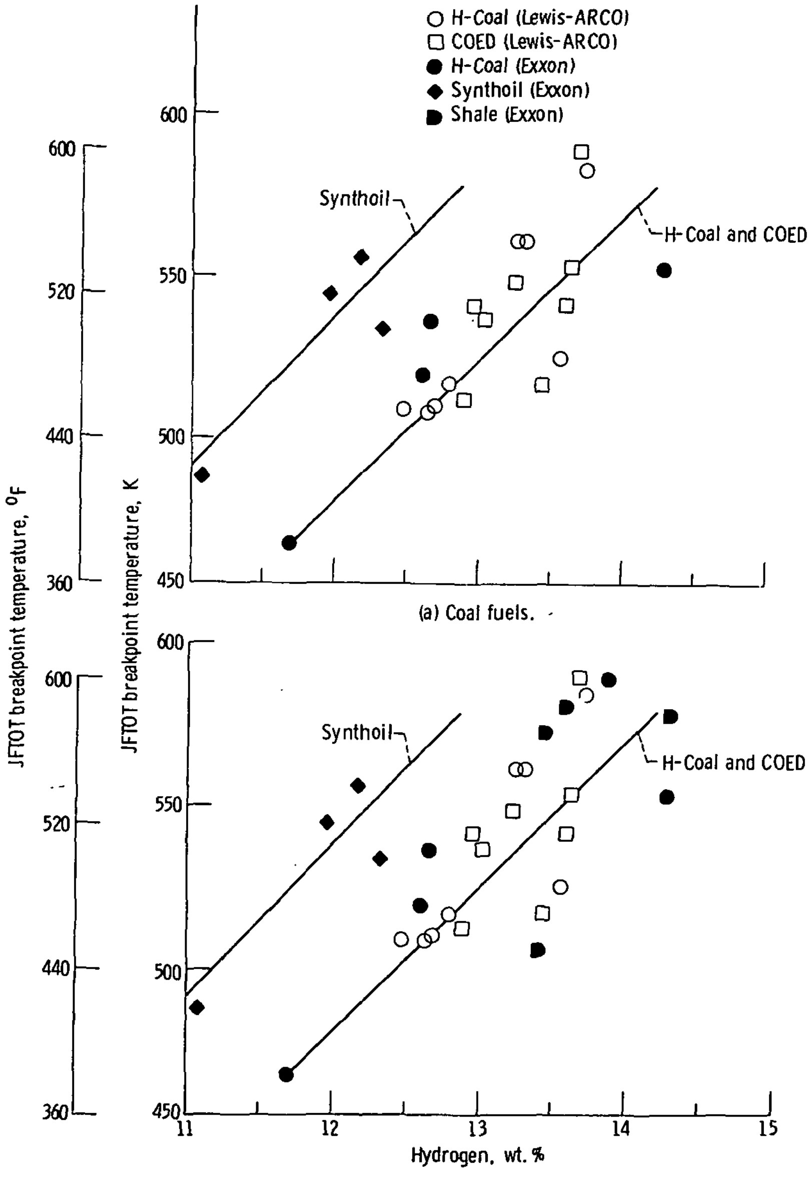


Figure 10. - Variation of JFTOT breakpoint temperature with nitrogen level after hydrotreatment.



(a) Coal fuels.

(b) Coal and shale fuels.

Figure 11. - Variation of breakpoint temperature with hydrogen content of low-nitrogen (≤67 ppm) fuels.

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