

## TRANSPORTATION FUELS FROM TWO-STAGE LIQUEFACTION PRODUCTS

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### INTRODUCTION

For several years, Chevron Research Company under a contract with the US Department of Energy has been studying the refining of coal liquids. Detailed results are given in a series of DOE Interim Reports (1). The earlier work emphasized upgrading of products from single-stage processes: SRC-II, H-Coal, and EDS. More recently, we have been studying products from two different two-stage processes: the Integrated Two-Stage Liquefaction (ITSL) Process and the Catalytic Two-Stage Liquefaction (CTSL) Process.

The purpose of this paper is to compare results for syncrudes from single-stage and two-stage processes, from different two-stage processes, from different coals [Illinois No. 6 (bituminous) and Wyodak (subbituminous)], and of different boiling ranges from a given coal and process.

The ITSL process, developed by Cities Service and Lummus Crest, Inc., operates with a high temperature (over 800°F) first stage with no added catalyst. The product is then deashed, and sent to a second-stage that operates at lower temperatures (typically below 800°F) with an ebullated catalyst bed (2).

The CTSL process, developed by Hydrocarbon Research, Inc. (HRI), operates with two catalytic ebullated-bed stages. In contrast to the ITSL process, the CTSL first stage operates at a lower temperature (below 800°F) than the second (which operates above 800°F) (3).

Depending upon how each liquefaction process is operated, the end point (EP) of the net whole-liquid product will vary. Typically, part or all of the vacuum gas oil (VGO) made by the process is used as recycle solvent for the coal. Some or all of it is ultimately converted to lower boiling products. Thus, the net whole-liquid product can have an EP ranging from below 650°F to over 850°F. As we will see, the ease or difficulty of upgrading is affected to a large extent by product EP. The 650-850°F VGO is relatively difficult to upgrade, but is reported to be an excellent recycle solvent. Therefore, there may be both upstream and downstream advantages to recycling this VGO, as shown for example, by MacArthur et al (4). Ultimately, of course, the costs and yields of both liquefaction and upgrading must be used to determine the optimum EP.

In this paper, we will use results for upgrading products from the H-Coal process (1, 5) as our primary basis for comparison with single-stage processes.

### FEEDSTOCKS

Key factors that determine how easy or difficult a particular syncrude is to refine are EP, boiling range, hydrogen content, and heteroatom content. Also, hot-heptane insoluble compounds (low-solubility polycyclic-aromatic and polar compounds, asphaltenes, and ash) can make syncrudes difficult to processes.

Table I shows properties of pairs of H-Coal and ITSL syncrudes derived from Illinois coal. Table II shows properties of pairs of H-Coal, CTSL, and ITSL syncrudes derived from Wyodak coal. In each case, the syncrude identified as "A" had a higher EP than that identified as "B". The A syncrudes were blended from components supplied HRI and Lummus in ratios recommended by DOE to represent, as nearly as possible, "net whole-liquid products" from these processes. [Note: the heavy fractions of Illinois ITSL A and Wyodak CTSL A, as-received, contained large quantities of hot-heptane insolubles and metals that presumably would not be part of the commercial net product. Therefore, the heavy fractions were redistilled to remove these impurities before the syncrude blends were prepared.] The B syncrudes were either fractions provided by DOE to represent product from lower-cut-point operation (Illinois ITSL B, Wyodak CTSL B), or redistilled from higher-boiling syncrudes (Illinois H-Coal B, Wyodak H-Coal B, Wyodak ITSL B). [Note that part of the front end was missing from the Wyodak ITSL oils.]

The distillation curves for the Illinois syncrudes are shown in Figure 1. The contrast between the boiling ranges of H-Coal and ITSL oils is quite striking. The H-Coal oil was quite low boiling--roughly 50% boiled below 400°F. The ITSL oil was considerably higher boiling--less than 20% boiled below 400°F, 70-75% boiled between 400 and 700°F.

Table I  
SYNCRUDES FROM ILLINOIS NO. 6 COAL

Process	<----H-Coal----->		<-----ITSL----->	
Sample Identification	A	B	A	B
LV% of As-Received Oil	100	87	95	69
<b>Inspection</b>				
Gravity, °API	25.8	28.1	13.6	17.6
Sulfur, ppm	2000	1400	865	700
Nitrogen, ppm	4600	3300	1050	730
Oxygen, ppm	18000	19600	2600	1800
Hydrogen, Wt %	11.29	11.44	10.19	10.68
Carbon, Wt %	86.25	86.13	89.35	88.99
Hot-Heptane Insolubles, ppm	3500	54	375	290
<b>TBP Distillation, °F (ASTM D2887)</b>				
St/5	56/177	56/170	97/275	97/214
10/30	213/333	200/310	375/532	314/471
50	404	380	602	560
70/90	476/588	440/508	665/745	609/676
95/99	654/765	538/589	793/859	703/763
<b>Boiling Range, LV%</b>				
St-400°F	49	57	12	18
400-700°F	48	43	69	76
700°F+	3	0	19	6

Table II  
SYNCRUDES FROM WYODAK COAL

Process	<-----H-Coal----->		<-----CTSL----->		<-----ITSL----->	
Identification	A	B	A	B	A	B
LV% of As- Received Oil	100	96	93	62	100*	52*
<b>Inspections</b>						
Gravity, °API	35.1	35.1	29.0	36.1	8.8	15.8
Sulfur, ppm	410	250	140	88	580	305
Nitrogen, ppm	1700	1500	1230	935	1670	1020
Oxygen, ppm	8500	6700	1500	1400	4600	3900
Hydrogen, Wt %	12.74	12.97	12.14	12.65	9.35	10.48
Carbon, Wt %	86.20	86.20	87.35	87.11	89.76	89.00
Hot-Heptane Insol., ppm	680	<10	216	54	180	80
<b>TBP Dist., °F (ASTM D2887)</b>						
St/5	53/156	52/165	69/184	56/179	295/353	295/340
10/30	173/261	178/269	216/375	206/312	449/587	363/538
50	354	356	478	397	653	587
70/90	429/535	424/509	566/706	470/539	710/790	623/668
95/99	602/785	542/603	771/858	571/634	840/941	689/731
<b>Boiling Range, LV%</b>						
St-400°F	60	57	34	51	**	**
400-700°F	38	43	55	49	8 (17)	13 (25)
700°F+	2	0	11	0	57 (58)	84 (73)
					35 (25)	2 (2)

\* Much of the front end (500°F-) was missing from the Wyodak ITSL oils. The missing fraction represented 24 LV% of the net liquid product for Syncrude A; 38 LV% for Syncrude B.

\*\* Numbers in parenthesis were corrected for the missing front end.

Figure 2 shows the distillation curves of the Wyodak oils. [Wyodak H-Coal B is omitted, because only 4% was removed by distillation. Therefore, its curve would lie close to that Wyodak H-Coal A, except for the EP which was much lower--603°F instead of 785°F.] Based on information supplied by Lummus, the ITSL curves were corrected to include the missing front end. As with the Illinois oils, the Wyodak H-Coal oil contained large amounts of naphtha; the Wyodak ITSL oil much more middle distillate. The CTSL oils were intermediate in boiling range and had a more even distribution than either the H-Coal or ITSL oils.

In general, the two-stage products contained fewer nitrogen- and oxygen-containing compounds than the single-stage products. [Exception: Wyodak ITSL A and Wyodak H-Coal contained about the same amounts of nitrogen.] The H-Coal oils contained considerably more hydrogen than the ITSL oils, and slightly more hydrogen than the

comparable CTSL oils. Probably, the higher hydrogen content was a result of the higher severity required for the single-stage process. In contrast, Figure 3 shows that within a given boiling range, the two-stage products had higher hydrogen contents than comparable H-Coal oils. Together, these two sets of observations may seem to present a paradox. However, the results are explained by the boiling distributions--the H-Coal oils contained more of the comparatively hydrogen-rich low-boiling components than the two-stage oils.

#### HYDROTREATING PILOT PLANT TESTS

**Discussion.** The major goals of the hydrotreating runs were either (1) to make specification jet fuel or diesel fuel and a naphtha suitable for catalytic reforming in a single hydrotreating step; or (2) to make a product suitable for hydrocracking in a second step.

To meet either goal, almost all of the heteroatom contaminants--sulfur, nitrogen, and oxygen--had to be removed by the hydrotreatment. Typically, the control target for product nitrogen content was 0.5 ppm or below. Sulfur is relatively easy to remove compared to nitrogen, and therefore was of little concern in this study. [Although sulfur is much easier to remove than nitrogen, the equilibrium concentrations of sulfur are somewhat higher than nitrogen in products hydrotreated in a single stage.] Oxygen-containing compounds can be as hard or harder to remove than nitrogen compounds. However, when the nitrogen was removed to 0.5 ppm, organic oxygen content was also removed to less than 10 ppm (based on limited analytical results). Most of the reported 50-100 ppm oxygen in the products was dissolved water.

In addition to removing the heteroatoms, it is necessary to hydrogenate most of the aromatics compounds in these fractions if finished jet fuel or diesel are to be the main products from a single hydrotreating step. One of the purposes of this work was to show the degree of aromatics saturation needed for specification diesel and jet fuel. The amount of hydrogen consumed will be determined by the hydrogen contents of the feed and products, and the amounts of heteroatoms removed.

If the hydrotreated product is to be hydrocracked, the hydrotreating severity can be somewhat less severe than if jet and diesel fuels are to be finished product. Additional hydrogen will be added in the second-stage hydrocracker.

**Catalyst Activity.** Table III briefly compares results of hydrotreating results for the syncrudes. The tests were made with a single catalyst, Chevron's commercial ICR-106 catalyst, at three different liquid hourly space velocities (LHSV): 0.5, 1.0, and 1.5 volumes of feed per volume of catalyst per hour, and a variety of hydrogen partial pressures and catalyst temperatures. The syncrudes are listed in approximate order of difficulty (easiest to hardest). All of the oils were not tested at a single set of conditions; therefore, some of the rankings were estimated using results of other tests described in our DOE reports (1). All of the first five syncrudes listed were comparatively easy to hydrotreat, and some rankings were close to one another.

Table III  
 HYDROTREATING TESTS WITH ICR 106 CATALYST  
 Syncrudes listed in increasing order of hydrotreating difficulty

LHSV	0.5	1.0	1.5	1.5	1.5	1.5
H <sub>2</sub> Pressure, psia.	2300	2300	2300	1800	1400	1000
<b>Wyodak CTSL B (EP=634°F)</b>						
Temperature, °F	680	705	715	715	715	715
H <sub>2</sub> Consumption, SCF/B	775	725	725	690	450	180
Product Nitrogen, ppm	0.5	<0.3	<0.3	<0.3	<0.3	<0.3
Product Aromatics, LV%	3	3	4	6	14	25
<b>Wyodak H-Coal A (EP=603°F)*</b>						
<b>Illinois H-Coal B (EP=589°F)</b>						
Temperature, °F		750	750			
H <sub>2</sub> Consumption, SCF/B		2000	1950			
Product Nitrogen, ppm		<0.3	<0.3			
Product Aromatics, LV%		2	5			
<b>Wyodak ITSL B (EP=731°F)</b>						
Temperature, °F	683					
H <sub>2</sub> Consumption, SCF/B	1650					
Product Nitrogen, ppm	<0.3					
Product Aromatics, LV%	14					
<b>Wyodak H-Coal A (EP=785°F)</b>						
Temperature, °F		750	750			
H <sub>2</sub> Consumption, SCF/B		1225	950			
Product Nitrogen, ppm		<0.3	<0.3			
Product Aromatics, LV%		3	13			
<b>Illinois ITSL B (EP=763°F)</b>						
Temperature, °F	710	730	745	745		
H <sub>2</sub> Consumption, SCF/B	1600	1400	950	600		
Product Nitrogen, ppm	<0.2	<0.2	0.4	6		
Product Aromatics, LV%	10	26	38	58		
<b>Illinois H-Coal A (EP=765°F)</b>						
Temperature, °F	750	750	750	750		
H <sub>2</sub> Consumption, SCF/B	2150	1600	1275	825		
Product Nitrogen, ppm	<0.3	0.3	10	50		
Product Aromatics, LV%	2	20	35	45		
<b>Wyodak CTSL A (EP=858°F)</b>						
Temperature, °F	750					
H <sub>2</sub> Consumption, SCF/B	825					
Product Nitrogen, ppm	0.3					
Product Aromatics, LV%	24					
<b>Illinois ITSL A (EP=859°F)*</b>						
<b>Wyodak ITSL A (EP=941°F)</b>						
Temperature, °F	750					
H <sub>2</sub> Consumption, SCF/B	1825					
Product Nitrogen, ppm	4					
Product Aromatics, LV%	42					

\* Rank estimated from tests at other conditions (Reference 1).

Some generalizations can be made, based on the ease of hydrotreating and feed properties:

(1) For a given boiling range, syncrudes from two-stage liquefaction are easier to upgrade than those made in one-stage--that is, lower hydrotreating severity is needed for a given product quality in upgrading. This result appears to be the effect of the lower heteroatom contents of two-stage syncrudes.

(2) For syncrudes from a given liquefaction process, relatively small increases in EP can make the syncrudes much harder to upgrade. For example, a good correlation (roughly linear) was found between required catalyst temperature and syncrude EP for a group of ITSL oils, regardless of coal source. For example, Wyodak ITSL B (EP = 634°F) could be hydrotreated at a temperature about 100°F lower than Wyodak ITSL A (EP = 941°F) for the same degree of heteroatom removal. [See Figure 4, Reference 6.]

Not surprisingly, the easiest oils to process were the three syncrudes with EPs below 650°F--Wyodak CTSL light oil (B), and the two redistilled H-Coal (B) oils. The CTSL appears to be the easiest of the three. Although it had a slightly higher EP than the others, it had the advantage of a lower heteroatom content.

Of the four oils with EPs between 700°F and 800°F, Wyodak ITSL oil B had the lowest EP and was easiest. Next is Wyodak H-Coal B. Although it had a slightly higher EP than the oils in this group, it had a much lower average boiling range. Illinois ITSL B ranked next. It was much easier than Illinois H-Coal A, which had about the same EP but a much higher heteroatom content.

Finally, of the three oils with EPs above 800°F, Wyodak CTSL oil A was clearly the easiest. Although its EP was about the same as Illinois ITSL A, it had a lower average boiling range and lower heteroatom content. Of all the oils, Wyodak ITSL A was the most difficult to process. It contained the most 700°F+ material of any of the syncrudes, and had the highest EP (941°F).

Catalyst Stability. The length of specific tests varied from several days to several months. With one exception and within the limits of the tests, ICR-106 catalyst appeared to stable for heteroatom removal during all of the tests shown in Table III. The exception: With Illinois H-Coal A, the catalyst lost about 20°F of activity during 1100-hr at 1.5 LHSV and 1800 psia hydrogen partial pressure. In contrast, Illinois ITSL B (with about the same EP as Illinois H-Coal A) was stable during a 900-hr test at the same conditions. The difference was probably due to the lower heteroatom and hot-heptane insolubles contents of the ITSL oil. [The higher EP oils were not tested at this pressure, but would be expected to cause appreciable catalyst deactivation also.]

#### YIELDS

For syncrudes with EPs below 800°F, there was relatively little cracking during hydrotreating, and the feed boiling range determined product boiling range (except for some EP reduction due to hydrogenation). As an example, Table IV contrasts yields of products from Illinois H-Coal A and Illinois ITSL B, two oils that have about the same EP but widely different boiling ranges.

Table IV  
HYDROTREATING TO 0.2 PPM NITROGEN (0.5 LHSV, 2300 psia H<sub>2</sub>)

Syncrude	H-Coal	ITSL
Catalyst Temperature, °F	750	710
Yields, Based on Fresh Feed		
C1-C4, Wt %	0.3	0.2
C5-250°F, LV %	20.4	7.0
250-350°F, LV%	26.3	6.8
350-550°F, LV%	57.7	53.6
550°F+, LV%	6.4	40.6
Total C5+, LV%	111	108
Chemical H <sub>2</sub> Consumption, SCF/B	2150	1600
Product Aromatics, LV%	2	12

For higher EP syncrudes, higher hydrotreating severities were required and more cracking occurred. Still, C1-C4 yields were low (2 LV% or below), indicating efficient use of the hydrogen.

#### PRODUCT PROPERTIES

General Comments. After hydrotreating, products of similar boiling ranges from the different liquefaction processes and different coals were quite similar. After removal of heteroatom-containing compounds, the products mainly consisted of cyclic hydrocarbons. The severity of hydrotreating determined the amount of hydrogenation of aromatics to naphthenes. There were, however, some differences. Products from subbituminous coals contained more paraffins than those from bituminous coals.

Naphtha. Hydrotreated and hydrocracked naphthas from coal liquids are excellent feeds for catalytic reformers because of the high content of cyclic compounds. Paraffin contents of all the hydrotreated naphthas were low, although the Wyodak naphthas contained somewhat more paraffins than those from Illinois coal as shown by Table V.

Table V  
PARAFFIN CONTENTS OF TYPICAL 150-350°F HYDROTREATED NAPHTHAS

<u>Feed Source</u>	<u>Paraffins, LV%</u>
Wyodak H-Coal	23
Wyodak ITSL	23
Wyodak CTSL	18
Illinois H-Coal	11
Illinois ITSL	7

At the higher hydrotreating severities, the cyclics in the naphthas were almost all hydrogenated. The naphthenes, however, could be dehydrogenated to high-octane aromatics by catalytic reforming at relatively mild conditions compared to those required for typical petroleum naphthas. Or, when reformed at higher severities, these naphthas would make extremely high octane products for gasoline blending or for chemicals production (benzene, toluene, and xylene). In the reforming process, much of the hydrogen consumed during hydrotreating would be recovered. [We have not performed catalytic reforming studies on naphthas from the two-stage processes, but

results would be expected to be similar to those previously reported for naphthas from single stage processes (7).]

**Jet.** To make jet fuel meeting the ASTM smoke point specification of 20 mm (minimum), most of the aromatics in the coal liquids had to be hydrogenated.

Figure 4 is a plot of smoke point versus aromatic content of kerosene jet fuels from the various syncrudes. The results fall into two rough groups, those from Wyodak coal and those from Illinois coal. At a given aromatics content, those from Wyodak coal had smoke points 2-3 mm higher than those from Illinois coal, a consequence of the higher Wyodak paraffin content. [The Wyodak jet contained about 10 LV% paraffins; the Illinois jet, 1-3 LV%.] The Illinois jet fuels met the jet smoke specification of 20 mm at 10% aromatics or lower; the Wyodak jet fuels met the specification at about 16 LV% aromatics. [Some of the scatter in results for products from a given coal was due to different boiling distributions. Those jet fuels containing more low boiling material had somewhat higher smoke points.]

Jet fuels from coal offer some unique advantages over those from petroleum. Because they contain high concentrations of naphthenes, they are very dense and have high heating values by volume. Therefore, they could have specialized uses, such as for military fuels. For example, Figure 5 shows the densities of narrow boiling fractions of hydrotreated ITSL oil. Jet fuel of a desired density could be made by adjusting the boiling range. The ASTM specification for jet fuel gravity is 37°API (minimum). However, this specification is probably unnecessary for aircraft with modern flow controllers, and lower gravity (higher density) fuels could be acceptable. Also, these jet fuels have unusually low freezing points, because of low normal paraffin contents.

**Diesel.** Diesel products from both single-stage and two-stage processes met typical ASTM specifications. A relatively high degree of hydrogenation was needed to meet the cetane-number specification of 40 (minimum).

Figure 6 shows the relationship for cetane number versus aromatics content for products from single-stage and two-stage processes. With the two-stage oils, the specification was met with an aromatics content of about 20 LV%; with single-stage oils, an aromatic content of less than 10 LV% was needed. These differences, however, were not necessarily the result of single-stage versus two-stage processing. Rather, they appear to be due to changes in boiling ranges of the diesels. For example, Table VI compares pairs of samples of different boiling ranges. The aromatics and paraffin contents within a given pair were about the same. Within each pair, the higher boiling sample had the higher cetane number. Also, in other comparisons (1), the more paraffinic diesels had higher cetane numbers, when other properties were about equal.

As with the jet fuels described above, these coal-derived diesel fuels had excellent cold weather properties, and high volumetric energy contents.

Table VI  
EFFECT OF BOILING RANGE ON CETANE NUMBER

Source	Initial, °F (TBP)	Midpoint, °F (TBP)	Cetane No.	Aromatics, LV,%	Paraffins, LV%
Wyodak CTSL	250	414	44.2	3.9	9.5
	350	454	48.7	4.6	7.7
Illinois ITSL	250	520	43.1	9.8	<1
	350	538	45.3	11.7	<1
Illinois H-Coal	250	393	35.9	15.6	3.6
	350	438	37.7	18.5	3.7

#### HYDROCRACKING RUNS

If the feed EP is below 775°F and if diesel fuel is a desired product, further cracking conversion of hydrotreated coal syncrude will probably not be necessary. The EP will be lowered somewhat due to hydrogenation, and little or no hydrotreated product will boil above the diesel range. However, if the feed EP is higher than 775°F or the desired products are either all-gasoline or a combination of gasoline and jet fuel, further conversion may be necessary. In a other papers (8, 9), we discussed in detail the hydrocracking of hydrotreated H-Coal and ITSL oils. Hydrocracking is a flexible process that can be varied to make only naphtha or a combination of gasoline and middle distillate. The products from hydrocracking coal oils are similar to those obtained from hydrotreating; the quantities of each can be varied, depending upon demand.

The liquid yields from hydrocracking were greater from ITSL syncrudes than those from H-Coal or CTSL syncrudes. This is because of the larger fraction of high boiling material in the ITSL syncrude, the lower hydrogen content, and--as a result--the greater volume expansion during hydrocracking. For example, the yield of C5+ naphtha was 115 LV% (based on fresh feed to the first-stage hydrotreater) when Illinois ITSL B was hydrocracked at 350°F recycle cut point, compared to 108 LV% from Illinois H-Coal A. Thus, 7 LV% more liquid was made from a given volume of ITSL syncrude than from H-Coal syncrude.

#### TWO-STEP HYDROTREATING OF HIGH EP SYNCRUDES

Specification jet and diesel fuels were made from all of the syncrudes with EPs below 775°F in a single-step by hydrotreating at relatively severe conditions. However, with the three high EP feeds listed at the bottom of Table III, the jet and diesel were either marginal or too aromatic to meet specifications directly--even at 0.5 LHSV and 2300 psia hydrogen pressure .

A series of experiments with Wyodak ITSL A (the most difficult syncrude), suggested an alternative upgrading route.

First, it was shown that the aromatic content increased rather than decreased when the catalyst temperature was increased from 750°F to 775°F. Then, it was shown that the aromatic content remained about the same when the LHSV was reduced by a factor of two (to 0.25 LHSV) and the temperature held constant. Together, these results indicated

that the equilibrium was unfavorable for hydrogenation of some of the high-boiling polycyclic-aromatic compounds at the run conditions.

Therefore, we tried a two-step approach: (1) Hydrotreat at relatively high temperature (e.g., 750°F) to remove most of the heteroatoms. (2) Further hydrogenate at lower temperatures (e.g., 600-650°F) for further aromatics saturation.

In the next test, product from the initial experiment (750°F, 0.5 LHSV, 2300 psia H<sub>2</sub>), which contained 42 % aromatics, was hydrotreated a second time using the same catalyst. The LHSV and pressure were kept the same, but the temperature decreased to 650°F--100°F lower than previously. Due to the more favorable equilibrium at 650°F, product aromatics were reduced to 12%. The jet and diesel fractions, respectively, exceeded smoke point and cetane number specifications. Also, enough EP reduction was achieved so that less than 5% of the product boiled above the diesel range.

When the temperature was further decreased to 600°F, the aromatic content of the product did not decrease further, but increased to 20%. [The rate of hydrogenation was lower, although the equilibrium was even more favorable than at 650°F.] The diesel fraction still met the cetane number specification, however.

The results show that two-step hydrotreating [with the second hydrotreatment at a relatively low temperature] is an alternative to the hydrotreating/hydrocracking route for upgrading high EP syncrudes, provided diesel fuel is a desired product.

#### CONCLUSIONS

Coal liquids produced in the ITSL and CTSL processes with EPs from about 600°F to over 900°F were hydrotreated to make diesel and jet fuels, and naphthas suitable for catalytic reforming to gasoline. Specific conclusions are as follows:

(1) Oils from two-stage processes were easier to upgrade than comparable boiling-range products from single-stage processes, due to lower nitrogen and oxygen contents. However, as with products from single-stage processes, relatively small increases in EPs made the oils much harder to upgrade.

(2) Except for modest differences in paraffin contents, properties of finished products of given boiling ranges from both Wyodak and Illinois coals, and both one- and two-stage processes studied were fairly similar, and mainly consisted of cyclic hydrocarbons. Products from Wyodak coal were somewhat more paraffinic than those from Illinois coal.

(3) Product boiling ranges were different, depending upon the liquefaction process and the cut point used in that process. The single-stage processes made more naphtha than the two-stage processes at a given cut point; the two-stage processes made more middle distillate. The ITSL process made more middle distillate than the CTSL process. Diesel products from two-stage processes had higher cetane numbers at a given aromatic content than those from single-stage processes. At least in part, this was due to product boiling range differences.

(4) In all cases studied, the jet fuel and diesel products had high densities and, therefore, high volumetric-energy contents.

(5) Wyodak CTSL light oil had a higher hydrogen content and lower heteroatom content than the other oils. These factors, plus its low EP, made it easier to upgrade than the other syncrudes studied.

(6) For high EP syncrudes, an attractive upgrading route is a two-step process--hydrotreating to remove most of the heteroatoms, followed by low-temperature hydrogenation to saturate aromatics.

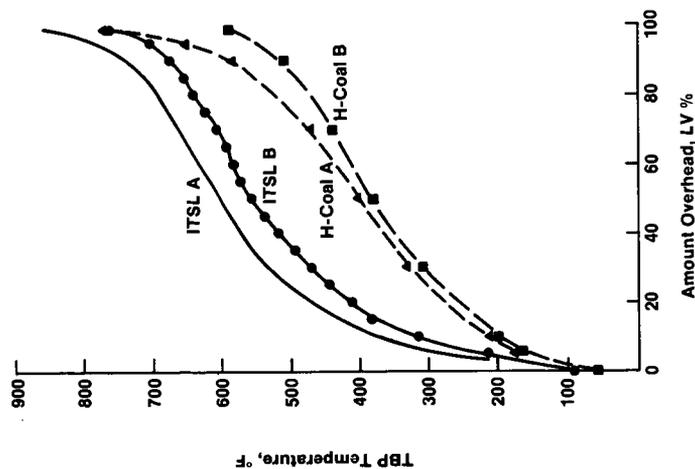
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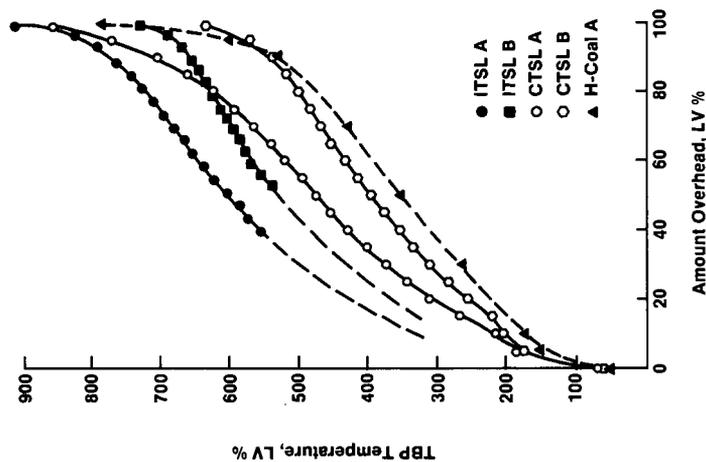
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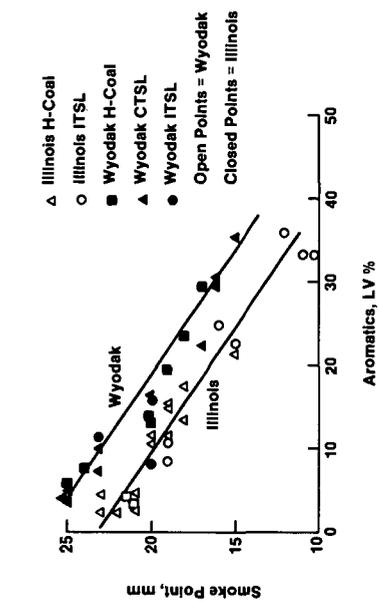
**FIGURE 1**  
**TBP DISTILLATIONS OF**  
**SYNCRUDES FROM ILLINOIS NO. 6 COAL**



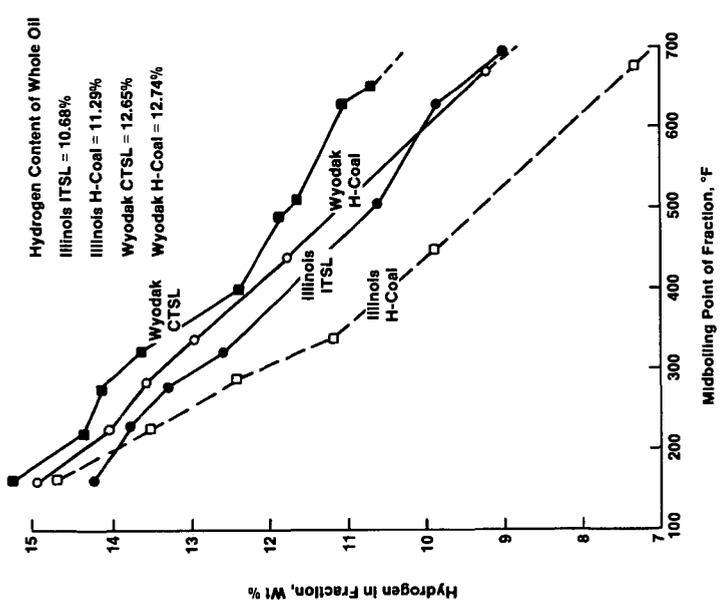
**FIGURE 2**  
**TBP DISTILLATIONS OF**  
**SYNCRUDES FROM WYODAK COAL**



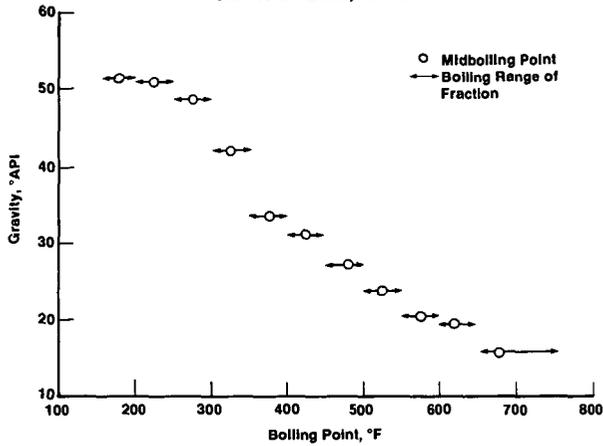
**FIGURE 4**  
**EFFECT OF AROMATICS ON**  
**SMOKE POINT OF JET FUELS FROM**  
**HYDROTREATED COAL-DERIVED FEED**  
**Boiling Range = 250-550°F or 250-600°F**



**FIGURE 3**  
**HYDROGEN CONTENT OF SYNCRUDE**  
**FRACTIONS VERSUS BOILING RANGE**



**FIGURE 5**  
**API GRAVITIES OF NARROW BOILING**  
**FRACTION OF HYDROTREATED ILLINOIS ITSL OIL**  
**Total Aromatics, 11 LV %**



**FIGURE 6**  
**EFFECT OF AROMATICS ON THE**  
**CETANE NUMBER OF DIESEL**  
**FUELS FROM HYDROTREATED COAL-DERIVED OILS**

